8-2015

Analysis of Countermovement Vertical Jump Force-Time Curve Phase Characteristics in Athletes

Christopher J. Sole
East Tennessee State University

Analysis of Countermovement Vertical Jump Force-Time Curve Phase Characteristics in Athletes

---

A dissertation

presented to

the faculty of the Department of Exercise and Sport Sciences

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Doctor of Philosophy in Sport Physiology and Performance

---

by

Christopher J. Sole

August 2015

Satoshi Mizuguchi, PhD, Chair

Kimitake Sato, PhD

Gavin L. Moir, PhD

Michael H. Stone, PhD

Keywords: Countermovement Jump, Force-Time Curve, Force Platform

ABSTRACT

Analysis of Countermovement Vertical Jump Force-Time Curve Phase Characteristics in Athletes

by

Christopher J. Sole

The purposes of this dissertation were to examine the phase characteristics of the countermovement jump force-time curve between athletes based on jumping ability, examine the influence of maximal muscular strength on the countermovement jump force-time curve phase characteristics of athletes, and to examine the behavior of the countermovement jump force-time curve phase characteristics over the course of a training process in athletes of varying strength levels. The following are the major findings of these dissertations. The analysis of athletes by jumping ability suggested that proficient jumpers are associated with greater relative phase magnitude and phase impulse throughout the phases contained in the positive impulse of the countermovement jump force-time curve. Additionally, phase duration was not found to differ between athletes based on jumping ability or between male and female athletes. The analysis of athletes based on maximal muscular strength suggested that only unweighted phase duration differs between strong and less-strong athletes. Interestingly, in both investigations based on jumping ability and maximal strength indicated the relative shape of the stretching phase representing the rise in positive force was related to an athlete's jumping ability (jump height). The results of the longitudinal analysis of countermovement jump force-time phase characteristics identified that these variables can be frequently assessed throughout a training process to provide information of regarding an athlete performance state. Furthermore, based on

the contrasting behaviors of many of the countermovement jump force-time curve phase characteristics over time, an athlete’s level of muscular strength may influence how these characteristics are expressed in the context of a training process.

DEDICATION

This work is dedicated to my family for their love and support.

ACKNOWLEDGEMENTS

Dr. Michael Stone - for providing me with the opportunity to come to ETSU and pursue my passion. Additionally, for all that you have accomplished for the field of sport science. Your dedication is unparalleled.

Dr. Satoshi Mizuguchi - for serving as my chairperson for this project, and laying the groundwork that made this project possible.

Dr. Kimi Sato - for your support, guidance, and comic relief over the past three years.

Dr. Gavin Moir - for first introducing me to sport science research and your continued support

Dr. Bill Sands - for being an inspiration to me as both a sport scientist and educator, and letting me borrow your force plate.

All of the athletes, coaches, and fellow students who participated in this project.

TABLE OF CONTENTS

Page

ABSTRACT....2

DEDICATION....5

ACKNOWLEDGEMENTS....6

LIST OF TABLES....10

LIST OF FIGURES....12

Chapters

1. INTRODUCTION....13

Dissertation Purposes....16

Operational Definitions....16

2. COMPREHENSIVE REVIEW OF LITERATURE....19

Vertical Jump as a Measure of Explosiveness....20

The Countermovement Vertical Jump....23

The Force-Time Curve....25

Characteristics of the Force-Time Curve....29

Training Related Alterations to the Force-Time Curve....30

The Use of Vertical Jump in Athlete Performance Monitoring....33

Conclusion....37

3. PHASE CHARACTERISTICS OF THE COUNTERMOVEMENT JUMP FORCE-TIME CURVE: A COMPARISON OF ATHLETES BY JUMPING ABILITY....38

Abstract....39

Introduction....40

Methods..41
Participants..41
Study Design..42
Data Collection 43
Statistical Analysis..47
Results..48
Force-Time Curve Phase Characteristics..48
Average Phase Comparisons...54
Discussion 57
References..63
4. THE INFLUENCE OF MAXIMAL ISOMETRIC STRENGTH ON COUNTERMOVEMENT JUMP FORCE-TIME CURVE PHASE CHARACTERISTICS IN ATHLETES 69
Abstract..70
Introduction..71
Methods..73
Participants..73
Study Design..74
Countermovement Jump Testing 75
Isometric Strength Testing...76
Data Analysis...77
Statistical Analyses 81
Results..81

Discussion....94
Practical Application....99
References....100
5. MONITORING COUNTERMOVEMENT JUMP FORCE-TIME CURVE PHASE CHARACTERISTICS: A CASE-STUDY....108
Abstract....109
Introduction....110
Methods....112
Study Design....113
Countermovement Jump Testing and Analysis....114
Estimates of Training Load....117
Statistical Analyses....118
Results....119
Discussion....126
Practical Application....131
References....132
6. SUMMARY AND FUTURE INVESTIGATIONS....138
REFERENCES....142
APPENDICES....163
Appendix A: ETSU Institutional Review Board Approval....163
Appendix B: Informed Consent Document....167
VITA....171

LIST OF TABLES

Table Page

3.1 Athlete Demographic Information 42

3.2 Test Re-Test Reliability Statistics for CMJ F-t Curve Phase Variables 46

3.3 Summary of Phase by Performance Group *Post Hoc* Interactions for Relative Magnitude....51

3.4 Summary of Phase by Performance Group *Post Hoc* Interactions for Relative Impulse 52

3.5 Summary of Phase by Performance Group *Post Hoc* Interactions for Shape Factor 52

4.1 Athlete Demographic Information 74

4.2 Strength Performance Groups and Allometrically Scaled IPF 75

4.3 Test Re-test Reliability Statistics for F-t Curve Phase Characteristics 80

4.4 ANOVA Results for Analysis of Male Athletes 82

4.5 ANOVA Results for Analysis of Female Athletes 83

4.6 Summary of Statistically Significant Post Hoc Interactions for Phase Duration for the Phase by Strength Interaction for Male Athletes 84

4.7 Summary of Statistically Significant Post Hoc Interactions for Phase Magnitude for the Phase by Jump Performance Interaction for Male Athletes 86

4.8 Summary of Statistically Significant Post Hoc Interactions for Phase Impulse for the Phase by Jump Performance Interaction for Male Athletes 87

4.9 Summary of Statistically Significant Post Hoc Interactions for Phase Magnitude for the Phase by Jump Performance Interaction for Female Athletes 89

4.10 Summary of Statistically Significant Post Hoc Interactions for Phase Impulse for the Phase by Jump Performance Interaction for Female Athletes 90

4.11 Summary of Statistically Significant Post Hoc Interactions for Shape Factor for the Phase by Jump Performance Interaction for Female Athletes 91

5.1 Athlete Descriptive Data and Criterion Relative Strength Measures....................................114

5.2 Results of the Reliability Analysis of CMJ F-t Curve Characteristics..................................121

5.3 Summary of Tau-U Analysis Between Training Periods 125

LIST OF FIGURES

Figure Page

2.1 The countermovement jump force-time curve..27

3.1 Diagram of the CMJ F-t curve...45

3.2 Plot of post hoc interaction effect for comparisons of shape factor between the stretching and leaving phases 53

3.3 Normalized resampled CMJ F-t curve phases by performance group....................................55

3.4 Normalized resampled CMJ F-t curve phases between male and female athletes 56

4.1 The isometric mid-thigh pull (IMTP) testing apparatus 77

4.2 The CMJ F-t curve phases 78

4.3 Plotted interaction between stretching and leaving phase shape factors observed in females athletes 92

4.4 Average unweighted (A), stretching (B) and acceleration-propulsion (C) phases for males (A1-C1) and female (A2-C2) athletes...93

5.1 Countermovement jump F-t curve 117

5.2 Modified Rating of Perceived Exertion scale with descriptive terms...................................118

5.3 Time-series plots of unweighted phase characteristics and training loads 122

5.4 Time-series plots of stretching phase variables and training loads.......................................123

5.5 Time-series plots of acceleration-propulsion phase variables and training loads.................124

CHAPTER 1

INTRODUCTION

Sport scientists and strength and conditioning practitioners commonly rely on tests of muscular performance to indirectly assess an athlete's performance state. The data provided by these tests are used to guide a training process and/or assess training outcomes. The vertical jump is a well-studied and commonly used assessment of lower-body neuromuscular performance (Klavora, 2000). Research has demonstrated strong relationships between performance in the vertical jump and other explosive movements such as Olympic-style weightlifting (Carlock et al., 2004), straight-line sprinting (Cronin & Hansen, 2005; Marques, Gil, Ramos, Costa, & Marinho, 2011; Peterson, Alvar, & Rhea, 2006), and change of direction movements (Barnes et al., 2007; Brughelli, Cronin, Levin, & Chaouachi, 2008; Peterson et al., 2006). Additionally, there exists a multitude of evidence linking measures of strength and explosiveness and vertical jump performance variables such as jump height, peak power and peak force (Kraska et al., 2009; Stone et al., 2003; Stone et al., 2004). Finally, some evidence suggests that vertical jump testing may even be used as a method of assessing neuromuscular fatigue (Andersson et al., 2008; Byrne & Eston, 2002; Gathercole, Sporer, & Stellingwerff, 2015; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; Gathercole, Stellingwerff, & Sporer, 2015; Hoffman, Nusse, & Kang, 2003).

Vertical jump testing has been found to require little familiarization, and possess sufficient measurement reliability (Moir, Button, Glaister, & Stone, 2004; Moir, Sanders, Button, & Glaister, 2005). Additionally, vertical jump testing is non-invasive and relatively non-fatiguing in nature, and can be easily preformed in a field or laboratory setting. Considering the practical nature of this measurement, vertical jump may be tested regularly during a training process resulting in minimal disruption in scheduled training. Consequently, frequently assessing vertical jump has been suggested as an effective method of athlete performance monitoring (Mizuguchi, 2012; Sole, Mizuguchi, Suchomel, Sands, & Stone, 2014). Routine assessment of vertical jump may provide useful information regarding the athlete's performance state, assessment of training progress and/or outcomes, or possibly evaluate and track recovery.

There are two predominant forms of vertical jump commonly used in sport science research and athlete performance testing; they are, the static jump and the countermovement jump (CMJ) (Markovic, Dizdar, Jukic, & Cardinale, 2004). The static jump is initiated from a semi-squat position, and involves no pre-jump countermovement. The CMJ is initiated from a standing position and involves a pre-jump countermovement where the jumper lowers their center of mass prior to the concentric/propulsive phase of the jump. Because of the pre-jump countermovement the CMJ is thought to involve what is known as the stretch-shortening cycle (SSC); a natural occurring muscle action believed to augment performance (Cavagna, Saibene, & Margaria, 1965). In general, performance in the CMJ is greater as compared to the static jump. There are numerous proposed theories as to the mechanisms underpinning this improved performance ranging from excitation-contraction dynamics to the mechanical properties of the musculotendinous unit (Bobbert, Gerritsen, Litjens, & Van Soest, 1996). Consequently, CMJ performance is the product of a complex interaction the physiological and mechanical characteristics of the neuromuscular system.

The criterion performance variable in vertical jump testing is commonly the outcome variable jump height; however, there exist a large number of variables used in characterizing vertical jump performance, especially when measured using a force platform (Linthorne, 2001). Of the extant literature examining vertical jump, instantaneous kinetic and kinematic variables such as the peak vertical ground reaction force and peak power are most commonly used. The effectiveness of the use of instantaneous variables in analyzing vertical jump performance has recently been questioned, as these variables represent or are calculated from, single data points throughout the movement's kinetic and kinematic history (Gathercole, Sporer, Stellingwerff, et al., 2015; Richter, O'Connor, Marshall, & Moran, 2014). Considering the redundancy of the neuromuscular system, in that individuals may employ varying movement strategies (such as increasing the time of force application) to achieve a desired outcome (e.g. jump height) jump performance may influenced by a variety of factors. If the goal of vertical jump testing is to determine the state of the neuromuscular system, instantaneous and outcome variables may fall short of elucidating specific movement strategies and/or neuromuscular capacities underpinning a jumper's performance. Therefore, additional variables or analyses may be required to adequately represent vertical jump performance beyond peak and instantaneous variables.

One promising method of charactering CMJ performance would be a qualitative and quantities analysis of the movement's force-time curve. Previous research has demonstrated that specific training adaptations result in not only changes in CMJ peak variables, but also alterations in the shape of the CMJ force-time (F-t) curve itself (Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010a, 2010b, 2010c). Unlike peak variables these changes in the profile of force production may provide a more in depth mechanistic understanding of changes in CMJ performance. Consequently, an analysis of the shape of force production during a CMJ may be an effective method of assessing an athlete's performance state.

In addition to an analysis of the shape of the CMJ F-t curve as a whole, the shape of force production could be further quantified through a detailed analysis of the characteristics of the individual phases of the CMJ F-t curve. These variables could provide a more complete picture of an athlete's explosive state, potentially improving the level of information gained from vertical jump testing in athlete performance monitoring. However, very few data exist regarding how these F-t curve characteristics relate to jump performance and/or the behavior of these variables in response to training. Thus, it is relatively unknown as to how CMJ F-t curve characteristics might be interpreted for use in practice.

Dissertation Purposes

1. To examine the characteristics of the countermovement jump force-time curve phases between athletes based on jumping ability.
2. To examine the influence of maximal muscular strength on countermovement jump force-time curve phase characteristics in athletes.
3. To examine the behavior of countermovement jump force-time curve phase characteristics over the course of a training process in athletes of varying strength levels.

Operational Definitions

1. Acceleration-propulsion phase: a phase of the countermovement jump force-time curve where the vertical ground reaction force is above system weight as the jumper extends the hips, knees, and plantar flexes the ankles to push off into the air.
2. Allometric scaling: the mathematical process of scaling a variable to account for a subject's body shape and size, whereby the absolute variable is divided by the body mass of the subject raised to the two thirds power.
3. Concentric phase: portion of the countermovement jump force-time curve corresponding to displacement of the jumper's center of mass in the positive direction.

4. Countermovement jump: a type of vertical jump involving a pre-jump countermovement.
5. Eccentric phase: portion of the countermovement jump force-time curve corresponding to displacement of the jumper's center of mass in the negative direction.
6. Eccentric rate of force development: a measure characterizing the rise in the vertical component of the ground reaction force during the eccentric phase of the countermovement jump.
7. Force-time curve phase characteristic: variables describing the duration, size, area, and shape of a phase of the force-time curve.
8. Force-time curve phase: a distinct period of a force-time curve.
9. Force-time curve: a graphical representation of force produced during a movement, where force is plotted on the y axis and elapsing time on the x axis.
10. Ground reaction force: the force exerted by the ground on an object.
11. Impulse: the area under the force-time graph, corresponding to the force-time integral.
12. Leaving phase: a phase of the countermovement jump force-time curve equal to the acceleration-propulsion phase minus net impulse.
13. Muscular Strength: the ability of the neuromuscular system to produce force.
14. Net impulse: the summation of a positive and negative impulse.
15. Phase duration: a temporal characteristic of a force-time curve phase, representing elapsed time.
16. Phase impulse: the area under the force-time graph of a specific phase of the force-time curve.
17. Phase magnitude: the relative size of a countermovement jump force-time curve phase, represented graphically as the height of the phase.

18. Propulsion-deceleration phase: a phase of the countermovement jump force-time curve where the jumper is no longer producing force greater than system weight and gravity has begun to decrease the vertical velocity achieved during the acceleration-propulsion phase.
19. Shape factor: a ratio of impulse relative to a rectangular shape formed around the impulse, bound by the height (magnitude) and width (duration) of the impulse.
20. Stretching phase: a phase of the countermovement jump force-time curve where the vertical ground reaction force exceeds system weight during the transition into the propulsive phase.
21. System mass: total mass of the jumper including clothing, shoes, etc.
22. System weight: the force resulting from the effect of gravity on system mass.
23. Time-normalization: to make a time-series conform to a norm or time standard.
24. Unweighted phase: a phase of a countermovement jump force-time curve where the vertical ground reaction force falls below system weight.

CHAPTER 2

COMPREHENSIVE REVIEW OF LITRATURE

Jumping is fundamental athletic movement common in the performance of many sports. In the field of sport science and strength and conditioning, testing the vertical jump ability is a commonly used method for indirectly assessing an athlete's performance level and functional state of the neuromuscular system. Vertical jump testing has been found to be reliable, relatively non-fatiguing, require minimal familiarization, and entail minimal risk (Cormack, Newton, McGuigan, & Doyle, 2008; Moir, Button, Glaister, & Stone, 2004; Moir, Garcia, & Dwyer, 2009; Moir, Shastri, & Connaboy, 2008). Previous research has reported relationships between vertical jump performance and other explosive movements such as straight-line sprinting and change of direction movements (Peterson, Alvar, & Rhea, 2006). The vertical jump test can also be adapted to assess an athlete's neuromuscular performance under different conditions, such as with the addition of external loads (Cormie, McBride, & McCaulley, 2008; Kraska et al., 2009; McBride, Triplett-McBride, Davie, & Newton, 1999), or by imposing specific constraints on the jumper such as controlling starting position depth, or eliminating the countermovement (Markovic, Dizdar, Jukic, & Cardinale, 2004). Finally, vertical jump has been suggested to be effective in assessing an athlete's level of neuromuscular fatigue (Byrne & Eston, 2002; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; Hortobagyi, Lambert, & Kroll, 1991), and has become popular among practitioners for monitoring an athlete's state of fatigue or recovery (Taylor, Chapman, Cronin, Newton, & Gill, 2012).

There exist a multitude of kinetic and kinematic variables commonly used in practice and research when characterizing vertical jump performance. Of particular interest in this dissertation are variables obtained directly from the force-time (F-t) history of the movement, in particular variables that characterize the size and shape of distinct portions or phases of the F-t curve itself. Variables that directly characterize the F-t curve are of interest for two primary reasons: 1) it is the size of the force production itself that determines the result of the jump, and 2) it has been theorized that the size and shape of the period of force production is the most valid indicator of muscular activity associated with its generation (Adamson & Whitney, 1971). Additionally, previous authors have suggested that an analysis of force production with respect to time (such as that provided with an analysis of F-t curve characteristics) may provide a mechanistic understanding of jump performance capable of delineating the nature and time course of training adaptation (Cormie et al., 2008; Cormie, McBride, & McCaulley, 2009; Cormie, McGuigan, & Newton, 2010a, 2010c). Moreover, of F-t characteristics impulse in particular has been suggested as the most appropriate variable for assessing explosive performance such as jumping (Adamson & Whitney, 1971; Knudson, 2009; Mizuguchi, 2012; Winter, 2005). Thus, an in depth analysis of a movements F-t curve and its characteristics may provide practitioners with an attractive method for monitoring and assessing athletes in training. The purposes of the following literature review are to 1) provide rationale for the use of vertical jump as a measure of lower-body explosive performance, 2) provide a brief review of the analysis of the F-t curve, 3) review the effects of training on vertical jump F-t curve characteristics, and 4) review the use of vertical jump testing as a method of monitoring athlete performance state.

Vertical Jump as a Measure of Explosiveness

Measuring vertical jump was first suggested as an assessment of human muscular performance by Sargent (1921). To date, the vertical jump test is one of the most commonly used (Taylor et al., 2012) and studied (Klavora, 2000) measures in athlete performance monitoring and sport science research. Aside from its practical nature, one potential rationale for the popularity of the vertical jump test is the relationships between performance in this test and other explosive movements reported throughout the extant sport science literature. For example numerous studies have reported relationships between performance in the vertical jump and performance in explosive movements such as sprinting (Berthoin, Dupont, Mary, & Gerbeaux, 2001; Bissas & Havenetidis, 2008; Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Cronin & Hansen, 2005; Peterson et al., 2006), and change of direction tasks (Barnes et al., 2007; Brughelli et al., 2008; Peterson et al., 2006). Researches have also reported relationships between vertical jump performance and specific sporting disciplines requiring explosive strength and high power output such as sprint cycling (Stone et al., 2004) and Olympic-style weightlifting (Carlock et al., 2004; Fry et al., 2006; Vizcaya, Viana, del Olmo, & Acero, 2009). Consequently, testing the vertical jump has become a popular method of indirectly measuring performance, and is also commonly used in talent identification. For example, Carlock and colleagues (2004) examined sixty-four national-level Olympic-style weightlifters reporting that vertical jump relative peak power (allometrically scaled to body mass) was strongly associated with a lifters current competition performance. Additionally, Fry et al. (2006) investigated performance variables capable of discriminating elite and non-elite weightlifters. Vertical jump height was found to be a significant contributor to the discriminant analysis, in identifying a lifters status as elite or non-elite.

In addition to explosive movements found in sport, relationships between vertical jump and several common measures of strength and explosiveness have been reported in the literature. Wisløff, Castagna, Helgerud, Jones, and Hoff (2004) reported strong correlations between maximal strength measured using a half squat and vertical jump height in male soccer players.

Several studies have reported similar results related to maximal dynamic strength and jump performance (Carlock et al., 2004; Haff et al., 2005; Haff et al., 1997; Nuzzo, McBride, Cormie, & McCaulley, 2008; Stone et al., 2003) indicating that maximal lower-body strength levels are reflected in many vertical jump performance variables. In addition to dynamic measures of strength, other measures of lower-body strength and explosiveness such as maximal isometric strength and dynamic and isometric rate of force development (Haff et al., 2005; Kawamori et al., 2006; Kraska et al., 2009; Nuzzo et al., 2008; Stone et al., 2004) have been found to reflect in an individual's vertical jump performance and vertical jump performance variables. For example, Kraska et al. (2009) reported moderate to strong relationships between isometric mid-thigh pull peak force and rate of force development and an athlete's jump height. Additionally, both isometric peak force and rate of force development were found to be associated with smaller decreases in jump height when comparing unweighted and weighted vertical jumps.

Relationships reported between vertical jump performance and other explosive movements are likely related to the common underlying mechanisms responsible for performance in both movements; specifically, characteristics of the neuromuscular system contributing to force production. One such characteristic is muscle fiber type and composition. Bosco and Komi (1979) in a study of thirty-four non-athletes reported magnitude of propulsive impulse, jump height, as well as rate of force development in both the static jump and CMJ were statistically related to a subject's percentage of type II fast-twitch muscle fibers. Similarly, in a study of Olympic-style weightlifters, Fry et al. (2003) found both weightlifting performance and vertical jump power to be significantly correlated with the presence of type IIa fibers and type II myosin heavy chain isoform content. In addition to fiber type and composition, the stimulation and excitation dynamics of the neuromuscular system are similar between vertical jump and many of these movements found to correlate with vertical jump performance. Ballistic and explosive-type muscular contractions have been shown to attain very high firing frequencies (Desmedt & Godaux, 1977), or the frequency at which the α-motor neuron transmits impulses. The frequency of neural impulses has been shown to influence both the magnitude (Enoka, 1995), and rate (Zehr & Sale, 1994) at which force is produced during muscle action. Therefore, similar neuromuscular strategies from an excitation-contraction perspective are employed in both vertical jumping and other explosive movements, thus influencing performance in both activities.

The Countermovement Vertical Jump

The two most commonly used vertical jump tests are the static and countermovement jumps (CMJ) (Markovic et al., 2004). The static jump is preformed from a semi-squat position without a preparatory countermovement. The CMJ is performed with an initial downward movement occurring immediately prior to the push-off phase of the jump. Because of this initial downward movement, the CMJ is believed to utilize the stretch-shortening cycle; a naturally occurring mechanism of coordinated muscle action found to improve performance (Cavagna, Saibene, & Margaria, 1965). Due to the involvement of this muscle action (the stretch-shortening cycle), performance in this test has been suggested as a means of assessing stretch-shortening cycle function (Lloyd, Oliver, Hughes, & Williams, 2011; Markovic et al., 2004).

In general, jumpers can achieve greater jump heights and power outputs during the CMJ as compared to the squat jump, even when achieving identical body positions during the push-off (Anderson & Pandy, 1993; Bobbert et al.,1996). This improved performance observed during the CMJ has been attributed to several potential mechanisms (Bobbert & Casius, 2005; Bobbert et al., 1996). It is theorized that a primary factor influencing performance in the CMJ is related to the development of active state in the associated musculature (Bobbert & Casius, 2005). According to this theory, the countermovement allows for greater cross-bridge formation prior the propulsive phase of the jump resulting in higher force production at the initiation of the propulsive phase of the movement. Additionally, it has been postulated that performance increases are related to the amount of time available for the neuromuscular system to develop force. The initiation of the countermovement and subsequent eccentric muscle action allows for increased time to develop force prior to concentric action, resulting in greater force generation at the initiation of the propulsive phase, in turn resulting in a greater performance. It has also been proposed that the countermovement results in a lengthening of the knee extensor and plantar flexors, placing the associated musculature in a more optimal region of the length-tension relationship (Gordon, Huxley, & Julian, 1966a, 1966b) resulting in improved force production at the initiation and throughout the movement (Ettema, Huijing, & de Haan, 1992). Utilization of stored elastic energy within and between musculotendinous structures is also thought to contribute to increased performance. The stretch of the musculotendinous unit induced by the countermovement and braking phase as the movement is reversed, results in energy storage in the series and parallel elastic elements of the tissues, which is later used to augment concentric action. Many of the tissues that compose the musculotendinous unit are capable of storing elastic energy, actively bound cross-bridges for example. However, tendon has been implicated as the primary contributor of elastic energy storage and utilization in mammalian running and jumping (Alexander & Bennet-Clark, 1977; Biewener & Roberts, 2000; Kawakami, Muraoka, Ito, Kanehisa, & Fukunaga, 2002; Kurokawa, Fukunaga, & Fukashiro, 2001; Kurokawa, Fukunaga, Nagano, & Fukashiro, 2003). Thus, it can be concluded that the primary source of stored elastic energy contributing to vertical jump performance is tendon. The involvement of spinal reflexes has also been suggested as a mechanism for the improved performance seen in the CMJ (Bosco, Tihanyi, Komi, Fekete, & Apor, 1982). The rapid stretch provided by the countermovement may result in activation of these reflexes, in turn increasing muscle activation and subsequently force production. Finally, the rapid stretch experienced by muscle during the countermovement may elicit the pre-stretch potentiation phenomenon of skeletal muscle, resulting in a stiffening of the tissue and subsequently augmenting performance (Rassier, 2009). From the above it can be concluded that the CMJ is a complex interaction of mechanical and physiological aspects of the neuromuscular system. Performance in the CMJ may reflect the functional state of one or more of these components. Consequently, the CMJ is capable of providing an array of information regarding the neuromuscular capacities and performance state of the jumper.

The Force-Time Curve

Measuring vertical jump using a force platform allows for indirect measurement of the force produced during the movement (Linthorne, 2001). Plotting force production with respect to time results in the creation of a F-t curve (figure 1). Examination of F-t curves as a means of analyzing human movement has been performed since at least the 1950s (Henry, 1952; Howell, 1956), and is recognized as an effective and insightful method of studying many athletic movement including vertical jumping (Payne, Slater, & Telford, 1968). Since its initial application, examination of a movement's F-t curve has been used as a method of evaluating performers of different levels and training backgrounds (Cormie et al., 2009; Hunebelle & Damoiseau, 1973; Laffaye, Wagner, & Tombleson, 2014; Ugrinowitsch, Tricoli, Rodacki, Batista, & Ricard, 2007), suggested as a diagnostic tool for evaluating and optimizing performance (Desipres, 1976; Dowling & Vamos, 1993; Henry, 1952; Hochmuth, 1984; Howell, 1956), and examined as a means of understanding the potential mechanisms underpinning training adaptations (Cormie et al., 2009; Cormie et al., 2010a; Cormie, McGuigan, & Newton, 2010b; Cormie et al., 2010c), and neuromuscular fatigue (Gathercole, Sporer, & Stellingwerff, 2015; Gathercole, Sporer, Stellingwerff, et al., 2015; Gathercole, Stellingwerff, & Sporer, 2015).

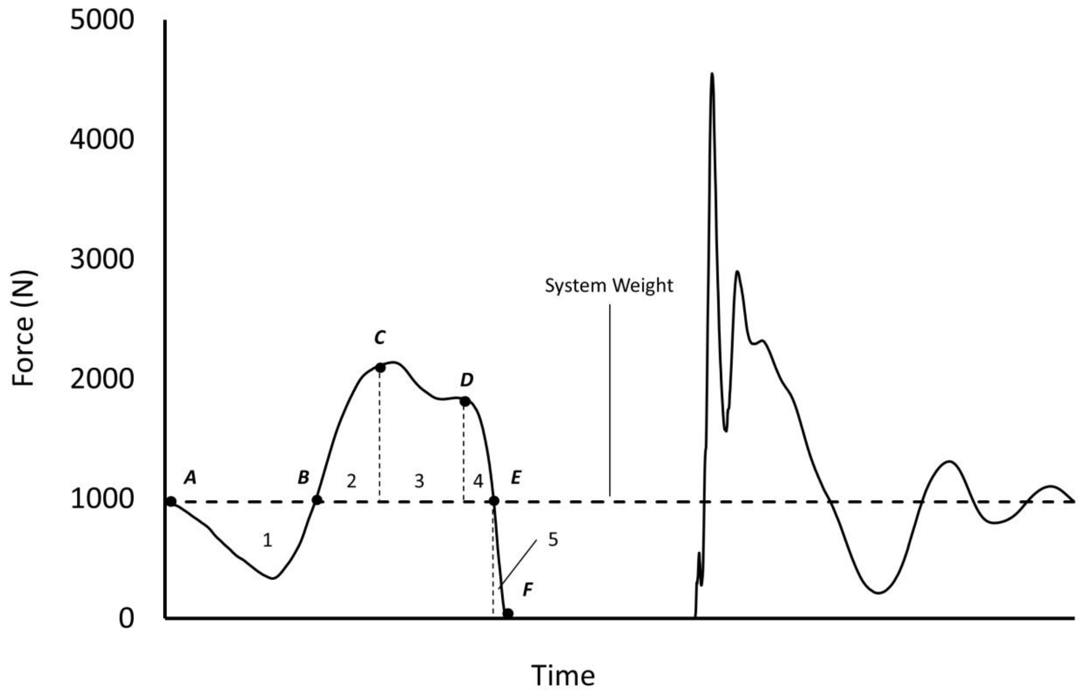

Figure 2.1 The countermovement jump force-time curve. Displays the vertical component of the ground reaction force during the countermovement jump. Point A: initiation of the unweighted phase, point B: time point where the vertical ground reaction force returns to system weight, point C: the end of the eccentric phase and initiation of the propulsive phase, as well as peak negative displacement of the jumpers center of mass, and the time point when center of mass velocity transitions from negative to positive, point D: peak velocity of the jumper's center of mass, point E: the vertical ground reaction force falls below system mass, point F: takeoff where the jumper leaves the force platform. Points A to B: unweighted phase, points B to C: stretching phase, points C to D: net impulse phase, points C to E: acceleration-propulsion phase, points D to E: leaving phase, points E to F: propulsion-deceleration phase. Area 1: unweighted impulse, area 2: stretching impulse, area 3: net impulse, combined areas 3 and 4: acceleration-propulsion impulse, area 4: leaving impulse, area 5: propulsion-deceleration impulse

Related specifically to the vertical jump, many early studies examined the shape and temporal characteristics (total time for example) of the F-t curve. Hunebelle and Damoiseau (1973) evaluated the length, height, and steepness of the entire positive impulse during a jump, and compared these variables between jumpers of different skill and developmental levels. The results of this investigation indicated less proficient jumpers produced a triangular shaped curve.

Additionally, the triangular curve was characterized by a long and slow rise in the positive impulse. Conversely, proficient jumpers produced a “steeper”, shorter duration positive impulse. The authors concluded that the assessment of F-t curves in training may prove a useful method for assessing and improving a movement; a conclusion previously noted by (Howell, 1956). In subsequent studies both Desipres (1976) and Miller and East (1976) provided additional evidence that more proficient jumpers produced a steeper rise and fall in positive impulse resulting in a steeper and more square shaped F-t curve. Moreover, Miller and East (1976) also observed less proficient jumpers regularly produced unimodal or single peaked curves as opposed to more proficient jumpers who achieved bimodal curves consisting of two peaks. In a study comparing the propulsive forces in weightlifting and vertical jumping Garhammer and Gregor (1992) noted qualitative and quantitative differences in the shape for the countermovement unweighted phase (figure 1- area 1) present between jumpers of different abilities. Specifically, poor jumpers typically exhibited “V” shaped unweighted phases where as “U” shaped unweighted phases were observed in better jumpers. The authors noted that altering the shape of the phase resulted in generation of greater impulse during this time period that translated to greater propulsive impulse and increased jump heights. The authors concluded by noting that changes in the shape of the F-t history may reflect changes in motor unit recruitment and “neural learning” of the jumper.

From these early studies the following can be concluded 1) the F-t curve seems to differ between performers of different abilities and development levels and so, it is likely these curves can be used as guide for optimizing the movement and/or assess performances, 2) early studies involving vertical jump have provided some general observations related to characteristics of several regions of the F-t curve (e.g. unweighted phase shape, “steepness” of the rise in force, shape of positive impulse, etc.) that seem to vary between jumpers of different development levels and jumping abilities.

Characteristics of the Force-Time Curve

When discussing the characteristics of the F-t curve we are essentially referring to the characteristics of the impulse generated during the movement. From Newton's Law of Inertia, we know that motion is the result of a change in the momentum of a body when acted on by a force. Therefore, in order for motion to occur force is necessary. However, it is important to understand that force is never applied instantaneously but rather over an interval of time. Thus, the kinetic variable impulse is used to describe force production with respect to time and consequently is relevant in discussions of all movement. Impulse is a convenient F-t curve characteristic as it can be easily represented graphically as the area under the curve itself. Numerically impulse is defined as the product of force and time, and mathematically as the integral of force with respect to time,

$$\text{Impulse} = \int_{t1}^{t2} \mathbf{F}dt \quad \text{(Enoka, 2008)}$$

where t_1 and t_2 define the time of force application (Enoka, 2008). Impulse has been strongly suggested as the most appropriate variable when characterizing brief explosive movements such as vertical jump (Adamson & Whitney, 1971; Knudson, 2009; Winter, 2005). The rationale for using impulse over all others variables can be explained by Newton's Law of Acceleration, specifically the impulse-momentum relationship. This relationship illustrates that the change in momentum of a body is equal to the impulse responsible for the change. From this perspective, the movement's kinetics and kinematics are joined and ultimately the net impulse produced during a jump is capable of exactly determining jump height. Thus, from a mechanical standpoint impulse is capable of explaining jump performance, whereas other performance variables only describe performance. Furthermore, as previously mentioned impulse and its characteristics provide information regarding the size, shape and development of force, which according to Adamson and Whitney (1971) likely provide the most accurate indication of the muscular activity responsible for the movement. Therefore, an analysis of impulse and its characteristics through careful examinations of the jumps F-t profile may provide the most valid indication of an athlete's explosive state, and perhaps aid in the elucidation of specific mechanisms underpinning performance. This dissertation will focus on four basic characteristics of the F-t curve or more specifically, phases of the F-t curve (figure 1). These specific characteristics are 1) duration, or length of the phase, 2) magnitude, or the height of the phase, 3) impulse, or the area of the phase, and 4) shape factor, a variable that represents the impulse of the phase relative to a rectangle drawn around the impulse, bound by the height (magnitude) and width (duration) of the impulse itself (Dowling & Vamos, 1993; Mizuguchi, 2012).

Training Related Alterations to the Force-Time Curve

Aside from information regarding instantaneous variables such as peak force, there is a paucity of detailed empirical evidence examining training-related alterations to shape of the F-t curve. Much of the information regarding this topic is the result of a series of studies performed by Cormie and colleagues (Cormie et al., 2009; Cormie et al., 2010a, 2010c). During these investigations the researchers utilized specialized analysis technique to create average F-t curves that were normalized to time. Through the use of this technique the researchers could then evaluate changes in the shape of the F-t curve between groups in response to training.

In one of the first of these studies Cormie et al. (2009) conducted an investigation to determine the impact of training on force-, velocity-, and power-time curves of the countermovement vertical jump. One aspect of the study was an examination of the effects of twelve weeks of power-focused training on relatively untrained individuals. Participants underwent a power-focused training program consisting of jump squats preformed at a load that maximized peak power. Following training, analysis of the averaged CMJ F-t curves revealed several significant differences between baseline and post-training. First, was a greater magnitude in the unweighted phase (figure 1- area 1) primarily caused by an increased displacement during this phase. Secondly, a significant increase in the rate of force development or steepness and magnitude of the initial rise in force in the approximate area of the stretching phase (figure 1- points B to C). Finally, power-focused training resulted in the occurrence of a bimodal force-trace consisting of two peaks in the area corresponding to positive impulse (figure 1- combined areas 2, 3, and 4). Specifically, following power-focused training a more pronounced first peak appeared in the F-t curve approximately in the area of the late stretching phase or early net impulse/acceleration propulsion phase (figure 1).

In a subsequent study, Cormie et al. (2010a) investigated the influence of ten weeks of either ballistic-type training or strength training on the magnitude of change and underlying mechanisms of athletic performance in relatively weak individuals. Ballistic-type training was comprised of maximal effort jump squats with between 0 and 30% of the subject's one-repetition maximum, while the strength training group preformed back squats with between 75% and 90% of one-repetition maximum. At post-test both groups exhibited significant improvements in jump height, peak force, rate of force development and net impulse. However, at mid-test only net impulse had significantly improved. In addition, time to take-off calculated as the initiation of the unweighted phase to the point of take-off (Figure 1 points A to F), decreased significantly in the ballistic-type training group at both mid- and post-test, and differed significantly from the strength training group at five weeks similar to rate of force development. Analysis of the normalized F-t curves revealed both training protocols resulted in significant alterations in the shape of the countermovement unweighted phase. Interestingly, the specific location of the alteration differed between training groups. The strength training group experienced a change later during the unweighted phase, whereas the power training group exhibited a difference throughout the entire phase. As previously mentioned there were no significant differences in peak force between groups at any time point. However, through visual analysis of the normalized curves from the post-training test, peak force is achieved earlier (i.e. first peak) in the power training group as compared to later (i.e. second peak) in the strength training group.

Finally, in a third investigation, Cormie et al. (2010c) investigated the influence of the initial strength levels of athletes on adaptations to power-focused resistance training. The study consisted of ten weeks of power-focused training performed by participants separated into two groups, strong and weak, based on their one-repetition maximum back squat relative to body mass. Following ten weeks both groups exhibited significant increases in CMJ height, peak force, rate of force development, and net impulse. When examining the averaged F-t curves, alterations were observed throughout the entire curve in both groups. Specifically, both groups experienced a significant increase in the magnitude of the unweighted phase, as well as significant increase in initial rise in force in the approximate areas of the countermovement stretching phase indicating an increased rate of force development. In addition, significant increases in force were found later in the movement; 63%-87% for stronger and 70.2%-79.2% of normalized time for the weak group. In combination with the increase in the rate of rise in force, a squaring of the force trace was observed in both groups, meaning the overall positive impulse became more square-like in shape. From the results of these studies we can conclude that along with changes in peak and instantaneous variables training elicits alterations in the overall shape of the F-t curve. Furthermore, these changes seem to vary based on type of training as well as on individual athlete characteristics such as initial strength levels.

The Use of Vertical Jump in Athlete Performance Monitoring

Athlete monitoring refers to the variety of activities employed by the coach, sport scientist, and the strength and conditioning practitioner as a means of characterizing the relationship between athlete performance and the demands of training and competition, and is a critical component of designing and implementing training (Sands, 1991; Stone, Stone, & Sands, 2007). In general athlete monitoring seeks to understand fatigue, recovery and adaptation in effort to gauge the athlete's performance state and better plan the training process. Because regular performance of maximal-efforts in competition-like settings/situations is impractical, an athlete's state is often assessed using various indirect measures of performance, such as field- and laboratory-based tests including vertical jump.

According to Taylor et al. (2012) vertical jump, specifically the CMJ is one of the most popular tests for performance monitoring among practitioners in high-level sport. Vertical jump is a commonly used test to assess neuromuscular function or the outcomes of a training process as evident by the myriad studies employing this measure. Vertical jump tests have also been commonly used as a test to track changes in athlete fitness throughout the competitive season

(Cormack, Newton, McGuigan, & Cormie, 2008; González-Ravé, Arija, & Clemente-Suarez, 2011; Gonzalez, Hoffman, Scallin-Perez, Stout, & Fragala, 2012; Granados, Izquierdo, Ibanez, Ruesta, & Gorostiaga, 2008; Häkkinen, 1993a, 1993b; Hoffman, Fry, Howard, Maresh, & Kraemer, 1991; Marques, Tillaar, Vescovi, & Gonzalez-Badillo, 2008; Newton, Rogers, Volek, Häkkinen, & Kraemer, 2006; Nimphius, McGuigan, & Newton, 2012; Thomas, Mather, & Comfort, 2014). Vertical jump tests have also been used to assess the acute effects and time course of recovery following training and competition in team sport athletes (Andersson et al., 2008; Cormack, Newton, & McGuigan, 2008; Coutts, Reaburn, Piva, & Rowsell, 2007; Hoffman et al., 2002; Hoffman, Nusse, & Kang, 2003; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010; McLellan, Lovell, & Gass, 2011; Nimphius, 2011; Oliver, Armstrong, & Williams, 2008; Ronglan, Raastad, & Børgesen, 2006; Thorlund, Aagaard, & Madsen, 2009; Thorlund, Michalsik, Madsen, & Aagaard, 2008), as well as individual-sport athletes (Balsalobre-Fernandez, Tejero-Gonzalez, & del Campo-Vecino, 2014a, 2014b; Girard, Lattier, Micallef, & Millet, 2006; Kraemer et al., 2001), and military personnel (Nindl et al., 2002; Welsh et al., 2008).

Despite the popularity of vertical jump as a test, there is little agreement as to which variable or variables are most important for the purpose of performance monitoring (Taylor et al., 2012). This problem is likely confounded by the fact that the importance of a measure is likely relative to the specific characteristic one is attempting to assess, and/or the sport and athlete being monitored. Additionally, there are conflicting reports in the extant literature regarding the effectiveness of many commonly used variables in reflecting an athlete performance state (i.e. fatigue or recovery). For example, the commonly used criterion measure of jump height has been found to reflect fatigue following both acute (Oliver et al., 2008) and prolonged (Nimphius, 2011; Ronglan et al., 2006) exposure to competition and training. Balsalobre-Fernandez et al. (2014a) reported statistically significant negative correlations between post-race CMJ height and both salivary cortisol and perceived exertion in middle and long distance runner. Similarly, Balsalobre-Fernandez et al. (2014b) reported significant relationships between CMJ height, salivary cortisol, and training load variables (perceived exertion, training zone, and total distance covered) over thirty-nine weeks of training in high-level middle- and long-distance athletes. Conversely, studies by several authors have reported vertical jump height alone was not sensitive enough to identify fatigue following competition (Cormack, Newton, & McGuigan, 2008; Krustrup, Zebis, Jensen, & Mohr, 2010) as well as periods of purposely intensified training (Coutts et al., 2007; Freitas, Nakamura, Miloski, Samulski, & Bara-Filho, 2014). Vertical jump F-t variables including peak and mean force, rate of force development, and power have been used to assess the effect of competition and neuromuscular fatigue, but again inconsistent results abound (Cormack, Newton, & McGuigan, 2008; Hoffman et al., 2002; Hoffman et al., 2003; McLellan et al., 2011; Thorlund et al., 2009). This inconsistency in sensitivity and behavior of vertical jump variables when utilized in assessing fatigue and recovery is highlighted by the results of Cormack, Newton, and McGuigan (2008). This particular study reported that only six of the eighteen vertical jump F-t variables examined declined immediately post competition in elite-level Australian rules football athletes. Furthermore, there was great variation in the patterns of behavior between variables during the recovery period (up to 120 hours post match).

It is important to note that many of the conflicting reports regarding vertical jump variable sensitivity could be related to discrepancies between athletes, or testing protocols (including instrumentation). However, one potential alternative explanation is the use of prominently peak and outcome variables. The human neuromuscular system possesses a high degree of redundancy, meaning that given a desired outcome (e.g. jump height), the system will find a way to produce the desired results by different means (e.g. different muscle activation patterns or different net joint moments). An example of this is how individuals have been shown to alter jump mechanics in the drop jump test based on the desired outcome (e.g. minimal ground contact time vs. maximal jump height) (Bobbert, Mackay, Schinkelshoek, Huijing, & van Ingen Schenau, 1986; Young, Pryor, & Wilson, 1995). It is quite possible that this concept could explain the some of the results of the above studies. Additionally, utilizing variables that include a timing component seems to provide more consistent information regarding the athlete's state. For example, the use of the flight-to-contraction time ratio used by several studies (Cormack, Newton, & McGuigan, 2008; Cormack, Newton, McGuigan, & Cormie, 2008; Nimphius, 2011). This variable avoids some of the potential limitations of instantaneous or outcome variables by factoring a timing component in turn providing additional information regarding the movement's mechanics, rather than simply the outcome. Specifically related to the CMJ, Gathercole and colleagues (Gathercole, Sporer, & Stellingwerff, 2015; Gathercole, Sporer, Stellingwerff, et al., 2015; Gathercole, Stellingwerff, et al., 2015) recently provided further information regarding the potential efficacy of alternative variables (such as eccentric and concentric duration, force at zero velocity, and the area under the force-velocity curve) focusing on mechanistic changes in the CMJ for identifying training-induced fatigue and adaptation. The results of these studies suggest that an athlete's performance state (fatigue or recovery) is reflected in both the movement (CMJ) output and strategy. Therefore, for the purpose of refining monitoring, practitioners should consider mechanistic variables in addition to typical (outcome and instantaneous) CMJ variables.

Conclusion

The purpose of this dissertation is to examine the use of CMJ F-t curve phase characteristics as a method of assessing an athletes' explosive performance state. From the above review of literature we can conclude the following: 1) the vertical jump performance test is a practical, reliable, and valid assessment of an individual's lower-body explosiveness, making it ideal for use in athlete performance monitoring settings, 2) considering the complex interplay of mechanical and neuromuscular aspects of the movement, the countermovement vertical jump is potentially capable of providing insight into the functional state of numerous areas of neuromuscular performance, 3) an in depth analysis of the F-t curve including both quantitative and qualitative aspects seems to be a promising method of examining vertical jump performance as well as elucidating the mechanisms underpinning both adaptation and fatigue.

CHAPTER 3

PHASE CHARACTERISTICS OF THE COUNTERMOVEMENT JUMP FORCE-TIME CURVE: A COMPARISON OF ATHLETES BY JUMPING ABILITY

Authors: [1]Christopher J. Sole, [1]Satoshi Mizuguchi, [1]Kimitake Sato, [2]Gavin L. Moir, and [1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Exercise Science, East Stroudsburg University of Pennsylvania, East Stroudsburg, PA, USA

ABSTRACT

The purpose of this study was to compare the phase characteristics of the countermovement jump (CMJ) force-time (F-t) curve between athletes based on jumping ability. On the basis of jump height, the top, middle, and lower 30 athletes (15 males and 15 females) were selected for analysis from a sample of 150 total athletes. Phases of the CMJ F-t curve were determined and characterized by their duration, magnitude, area (impulse), and shape. A series of three-way mixed ANOVAs were used to determine statistical differences in phase characteristics between performance groups as well as males and females. The results indicate proficient jumpers are associated with greater phase magnitude and impulse. Additionally, there existed no differences in phase duration or shape between male and female athletes.

Keywords: Force-time curve, countermovement jump, jump height, shape factor

Introduction

The countermovement jump (CMJ) is reliable, non-invasive, and relatively non-fatiguing assessment commonly used in athlete performance monitoring [13, 26, 33-35, 42]. Along with the standard variable of Jump height (JH), CMJ performance is commonly characterized using instantaneous variables such as peak force, peak velocity, and peak power. Although effective indicators of performance, these variables are limited in that they represent or are calculated from single points throughout the entire kinetic and kinematic history of the movement. Consequently, examinations of CMJ using only instantaneous variables provides limited mechanistic insight into the movement or neuromuscular characteristics responsible for the performance [37].

Throughout the force-time (F-t) curve of the CMJ, valuable information is contained regarding kinetic and temporal characteristics of the movement. Analysis of the F-t curves of athletic movements, CMJ in particular, has received considerable attention in biomechanics and sport science research. Previous research has investigated the relationships of factors such as training background and jumping ability on characteristics of the CMJ F-t curve [6, 10, 12, 18, 22, 31, 43]. Additionally, researchers have investigated the influence of specific neuromuscular training interventions on the CMJ F-t curve variables [6-9]. The results of the aforementioned studies suggest that differences can be observed in both instantaneous variables as well as in the actual shape of the F-t curve. Furthermore, alterations in F-t variables following training interventions may be specific to the type of training performed (e.g. strength- vs. power-based training) [7]. Collectively, the results of these investigations suggest the qualitative analysis of the CMJ F-t curve, may serve as an effective diagnostic tool for evaluating a performer and/or performance monitoring. Moreover, this form of analysis is attractive due to its potential capability of providing a better mechanistic understanding of performance; something difficult to accomplish when using only instantaneous variables.

Although the previously mentioned studies do provide information regarding F-t curve characteristics between jumpers and in response to training, they are limited by their general approach to examining the F-t curve itself. For example, Cormie and colleges [5-7, 9] examined the CMJ F-t curve in its entirety; while others [22, 43], assessed larger portions or curve characteristics that encompass multiple aspects of the movement (e.g. eccentric and concentric phases). Perhaps evaluation of the CMJ F-t curve may be enhanced through assessing the curve with increased precision. Analysis of the F-t curve on a phase by phase basis may enhance the use of these curves in evaluating CMJ performance. Detailed information regarding the characteristics of the F-t curve phases (duration, size, shape) as they relate to performance (i.e. JH) may greatly increase the extent to which the F-t curve may be used as a diagnostic tool. Unfortunately, little information exists regarding the individual and phase by phase characteristics of CMJ F-t curves. Thus, the purpose of the study was to compare CMJ F-t curves between athletes in an effort to identify how these phase characteristics relate to jumping ability.

Methods

Participants

Data from 150 athletes (age = 20.3 ± 1.3 y, body mass = 75.0 ± 13.3 kg, height = 175.6 ± 9.8 cm; male, n = 75, age = 20.5 ± 1.4 y, body mass = 82.0 ± 11.3 kg, height = 182.1 ± 7.4 cm; female, n = 75, age = 20.1 ± 1.1 y, body mass = 68.1 ± 11.3 kg, height = 169.1 ± 7.1 cm) were included in this study. All athletes were competitive at the National Collegiate Athletic Association (NCAA) Division I level representing various sport disciplines (table 3.1). All athlete data were previously collected as part of an ongoing athlete performance monitoring program. Data included in the present study were approved by the East Tennessee State University Institutional Review Board.

Table 3.1 Athlete Demographic Information

	Sport	n	Age (y)	Body Mass (kg)	Height (cm)
Males	Baseball	24	20.0 ± 1.3	83.2 ± 8.4	181.7 ± 6.3
	Basketball	11	21.0 ± 1.3	89.0 ± 12.4	188.7 ± 6.3
	Soccer	21	21.0 ± 1.5	77.9 ± 8.8	180.1 ± 6.9
	Tennis	6	20.9 ± 1.7	72.6 ± 8.2	180.0 ± 4.9
	Track and Field				
	Jumps	7	20.6 ± 1.6	78.9 ± 9.3	186.6 ± 4.9
	Throws	4	20.6 ± 1.1	99.2 ± 19.2	188.8 ± 6.6
	Multi-Event	2	19.4 ± 1.4	77.1 ± 5.7	183.0 ± 9.9
Females	Soccer	20	20.0 ± 1.0	67.1 ± 4.8	167.8 ± 4.8
	Softball	23	20.5 ± 0.9	69.1 ± 8.2	167.1 ± 6.9
	Volleyball	19	19.6 ± 0.9	69.7 ± 7.6	174.1 ± 7.1
	Track and Field				
	Jumps	8	20.0 ± 1.5	58.7 ± 5.1	163.9 ± 7.4
	Throws	2	19.7 ± 0.4	100.6 ± 43.3	174.5 ± 3.5
	Sprints	3	20.9 ± 1.3	60.1 ± 6.1	166.3 ± 10.1

Note: Values are expressed as means ± standard deviations

Study design

To investigate differences in CMJ F-t curve phase characteristics based on jumping ability, athletes were first separated into three performance groups based on jumping ability. The initial samples of 75 males and 75 females were independently ranked in ascending order based on testing session JH. From the ranked sample the top (high performance group [HPG]), middle (middle performance group [MPG]), and lower (low performance group [LPG]) fifteen males and females were selected to form the performance groups, totaling 90 athletes. The remaining sixty athlete's data were not further used in this analysis. Mean JH values for performance groups were HPG = 41.7 ± 6.7 cm (males = 47.4 ± 4.4 cm, females = 36.0 ± 2.1 cm), MPG = 31.9 ± 4.7 cm (males = 36.4 ± 1.5 cm, females = 27.5 ± 0.9 cm), and LPG = 24.1 ± 5.0 cm (males = 28.4 ± 2.4 cm, females = 19.7 ± 2.3 cm). A two-way analysis of variance (ANOVA) was used assess differences in JH between performance groups. Jump height was found to be statistically different between both performance groups and sex (performance group: $F(2,89) = 370$, $\eta^2 = 0.637$, $p < 0.001$, sex: $F(1,89) = 333$, $\eta^2 = 0.287$, $p < 0.001$). Additionally, there was no statistically significant group by sex interaction effect present. The results of this analysis support the author's decision to independently rank male and female athletes when forming performance groups in order to not over-represent one sex in any one performance group.

Data collection

Prior to testing, athletes performed a standardized warm-up routine consisting of 20 jumping-jacks, one set of five dynamic mid-thigh pulls with an unloaded 20 kg barbell and three sets of five mid-thigh pulls with 60 kg for males and 40 kg for females [21]. Countermovement jump testing consisted of athletes performing a specific warm-up of two submaximal CMJs performed at 50% and 75% of their perceived maximal effort. Athletes then performed two maximal effort CMJs with approximately 60 seconds allowed between trials. All jumps were performed on a uniaxial force platform (91.0 cm x 91.0 cm, Rice Lake Weighing Systems, Rice Lake, WI, USA) imbedded into the laboratory floor. To prevent arm swing and only measure lower body performance [23], athletes performed all jumps while holding a nearly weightless (< 1 kg) plastic bar as described by previous researches [4, 21, 28, 38]. The analog signal from the force platform was collected using an analog-to-analog BNC interface box (BNC-2110), and 16-bit analog-to-digital board (NI PCI-6036E, National Instruments, Austin, TX, USA). All trials were collected at a sampling frequency of 1000 Hz, as sampling frequencies of this magnitude have been suggested when measuring jump height using a force platform [29, 40]. Voltage data obtained from the force platform were converted to vertical ground reaction force using regression equations from regular laboratory calibrations [36] and F-t curves were constructed. All data collection and analysis were performed using custom programs (LabVIEW Version 12.0, National Instruments, Austin, TX, USA). To reduce random noise, all ground reaction force data were filtered using a fourth-order low-pass Butterworth digital filter [45] with a cutoff frequency of 40 Hz. [46, 47].

From the CMJ F-t curve, the following phases (figure 3.1) were determined based on previous research [19, 25, 32, 43]: the unweighted phase, the stretching phase, the net impulse phase, the acceleration-propulsion phase, the leaving phase, and the propulsion-deceleration phase. The following variables were calculated for each phase of the CMJ F-t curve (figure 3.1): 1) duration, calculated as the length of the phase in milliseconds, 2) magnitude, calculated as the height of the phase in newtons (N), 3) impulse, calculated through integration of the normalized (ground reaction force minus system weight) F-t curve of the phase and expressed in newton-seconds (Ns), and 4) shape factor, calculated as a ratio of impulse of the phase relative to a rectangle shape formed around the impulse, expressed as a percentage [11, 32]. Phase magnitude and impulse were scaled to the system weight of the jumper and expressed as newtons per kg ($N \cdot kg^{-1}$) and newton-seconds per kg ($Ns \cdot kg^{-1}$), respectively.

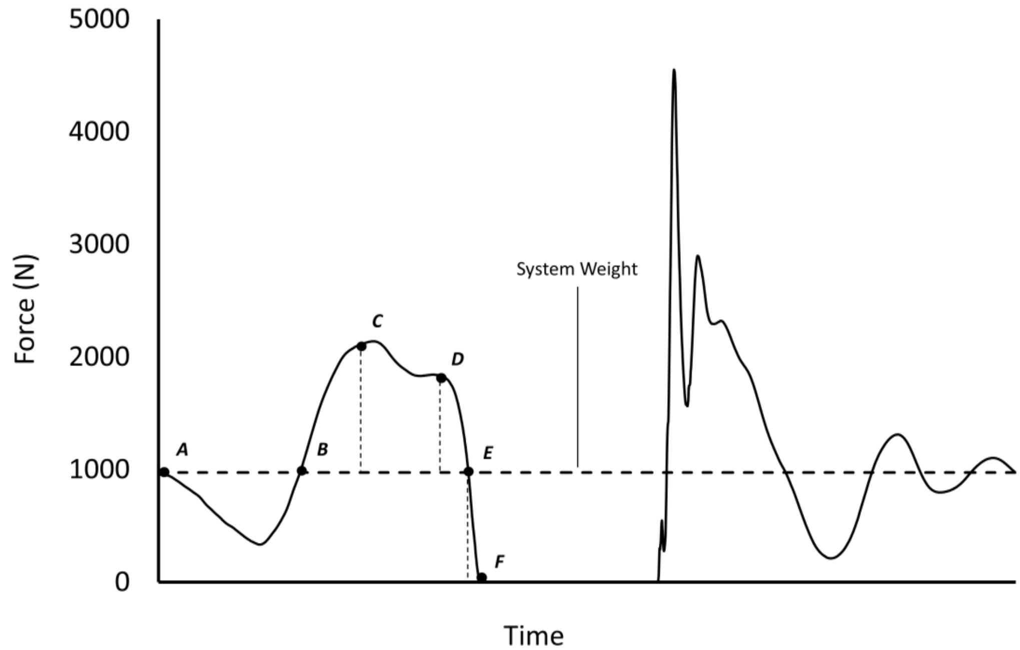

Figure 3.1 Diagram of the CMJ F-t curve. Points A to B: unweighted phase, points B to C: stretching phase, points C to D: net impulse, points C to E: acceleration-propulsion phase, points D to E: leaving phase, and points E to F: deceleration-propulsion phase

Test-retest reliability was assessed using an intraclass correlation coefficient (ICC) calculated for each variable. Additionally, random error was assessed through calculations of typical error expressed as a coefficient of variation (CV) [17]. ICC and CV for JH measures ranged from 0.900 - 0.993 and 1.8 - 3.2 % respectively throughout data collection. Test re-test reliability statistics of CMJ F-t curve phase characteristics are displayed in table 3.2. In order to reduce random error and to reveal a more typical score, the average of the two maximal CMJ trials was used in analyses for each variable [14].

Table 3.2 Test Re-Test Reliability Statistics for CMJ F-t Curve Phase Variables

Variable and Phase		CV%	ICC	95% CL
Duration	UW_{dur}	7.8	0.878	[0.815, 0.920]
	STR_{dur}	9.5	0.846	[0.775, 0.896]
	NI_{dur}	6.3	0.879	[0.822, 0.919]
	AP_{dur}	6.8	0.829	[0.751, 0.884]
	LV_{dur}	6.2	0.934	[0.902, 0.906]
	PD_{dur}	5.9	0.917	[0.876, 0.944]
Magnitude	UW_{mag}	10.8	0.891	[0.839,0.927]
	STR_{mag}	15.3	0.750	[0.643, 0.828]
	NI_{mag}	5.5	0.957	[0.936, 0.972]
	AP_{mag}	5.5	0.957	[0.936, 0.972]
	LV_{mag}	3.9	0.962	[0.943, 0.975]
	PD_{mag}	0.9	0.998	[0.997, 0.999]
Impulse	UW_j	6.7	0.939	[0.909, 0.960]
	STR_j	6.8	0.941	[0.911, 0.961]
	NI_j	2.6	0.991	[0.987, 0.984]
	AP_j	2.3	0.993	[0.989, 0.995]
	LV_j	8.4	0.950	[0.924, 0.966]
	PD_j	8.0	0.957	[0.717, 0.867]
Shape Factor	UW_{sf}	6.6	0.777	[0.493,0.744]
	STR_{sf}	7.7	0.796	[0.706, 0.861]
	NI_{sf}	4.1	0.864	[0.800, 0.908]
	AP_{sf}	5.9	0.825	[0.745, 0.881]
	LV_{sf}	2.3	0.773	[0.674, 0.844]
	PD_{sf}	2.8	0.804	[0.936, 0.972]

Note: UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase, $_{dur}$ = duration, $_{mag}$ = magnitude, $_{j}$ = impulse, $_{sf}$ = shape factor, CV = typical error expressed as a coefficient of variation, ICC = intraclass correlation coefficient, 95% CL = 95% confidence limits

Comparisons of CMJ F-t curve phases were performed using a re-sampling technique similar to that used by previous researchers [5-9]. Briefly, the F-t curves of each phase were modified to equal number of samples by adjusting the time delta between samples and resampling the signal. Once complete, all curves were expressed over an equal number of data points. With each curve consisting of an equal number of data points, curves could then be expressed as a percentage (0 - 100%) of the phase. With data normalized to time, comparisons could be made between jumpers at each time point throughout individual phases. Following resampling, the mean sampling frequency for the modified phase curves were 633 ± 125 Hz.

Statistical analysis

Four three-way mixed ANOVAs (three groups by two sexes by six phases) were used to determine statistically significant differences between levels of the independent variables. Effect size estimates for main and interaction effects were calculated using eta squared (η^2) [24]. Simple *post hoc* interaction tests were performed when necessary with the experimental type I error rate controlled using the Scheffe's adjusted *F* value [41]. For the comparison of phase F-t curves, all normalized curves were aggregated by performance group and expressed as a single curve. To determine statistical differences between curves, 95% confidence limits were calculated for each data point along the averaged curves and plotted to form upper and lower control limits. All statistical analyses were performed using Statistical Package for Social Sciences (IBM SPSS Statistics for Windows, Version 22.0, IBM Corp., Armonk, NY). Statistical significance for all analyses was set at $p \leq 0.05$. Holm's simple sequential rejective test [16] was used to adjust the critical p value from $p \leq 0.05$ in order to further control for type I error associated with the multiple 3-way mixed ANOVAs.

Results

Force-time curve phase characteristics

Three-way mixed ANOVAs showed statistically significant phase main effects for all variables (duration: $F(2.91, 244) = 1679$, $\eta^2 = 0.914$, $p < 0.001$, relative magnitude: $F(2.05, 244) = 395$, $\eta^2 = 0.573$, $p < 0.001$, relative impulse: $F(1.79, 244) = 7830$, $\eta^2 = 0.949$, $p < 0.001$, shape factor: $F(2.90, 244) = 340$, $\eta^2 = 0.730$, $p < 0.001$) The phase by performance group interactions were statistically significant for relative magnitude ($F(4.11, 172) = 15.5$, $\eta^2 = 0.044$, $p < 0.001$), relative impulse ($F(3.33, 139) = 43.3$, $\eta^2 = 0.010$, $p < 0.001$), and shape factor ($F(5.81, 243) = 3.60$, $\eta^2 = 0.015$, $p = 0.002$), but not duration. Phase by sex interactions were statistically significant for both relative magnitude ($F(2.05, 172) = 12.3$, $\eta^2 = 0.017$, $p < 0.001$), and relative impulse ($F(1.66, 139) = 55.2$, $\eta^2 = 0.006$, $p < 0.001$), but not for duration or shape factor. The phase by sex by performance group and performance group by sex interaction effects were not statistically significant for any variable. While the presence of an interaction effect warns that a main effect is contingent on another main effect, estimates of effect size (η^2) found from the analysis indicated that 57.3% - 95.0% of the variance in all the variables can be attributed to the phase main effect. Therefore, *post hoc* simple comparisons were performed to identify where statistically significant differences occurred. *Post hoc* pairwise comparisons, revealed all dependent variables were statistically different between phases with the exception of shape factor when comparing the unweighted phase to the stretching phase ($p = 0.911$), and stretching phase to the propulsion-deceleration phases ($p = 1.00$).

Post hoc simple phase by sex interaction comparisons (two phases x two sexes) showed common patterns for all simple interactions that were found statistically significant. For relative phase magnitude, this pattern was that male and female athletes both showed similar cell means for the unweighted phase, and an increase in cell means from the unweighted phase to the stretching, net impulse, and acceleration-propulsion phases. However, male athletes consistently exhibited a greater increase than females from the unweighted phase (males: 6.77 ± 1.53 $N \cdot kg^{-1}$ vs. females: 6.77 ± 1.57 $N \cdot kg^{-1}$) to the stretching (males: 13.43 ± 3.24 $N \cdot kg^{-1}$ vs. females: 11.74 ± 2.63 $N \cdot kg^{-1}$), net impulse (males: 14.24 ± 2.54 $N \cdot kg^{-1}$ vs. females: 12.29 ± 2.51 $N \cdot kg^{-1}$), and acceleration-propulsion phases (*identical to net impulse magnitude*). When transitioning from the net impulse and acceleration-propulsion phases to the leaving phase, male and female means decreased back to similar values (leaving: males: 9.19 ± 0.09 $N \cdot kg^{-1}$ vs. females: 8.67 ± 0.98 $N \cdot kg^{-1}$). However, considering males exhibited greater means in the net impulse and acceleration-propulsion phase the males decreased to a greater extent. A similar result was produced when comparing the stretching, net impulse, and acceleration-propulsion phases to the propulsion-deceleration phase (males: 9.80 ± 0.05 $N \cdot kg^{-1}$ vs. females: 9.78 ± 0.06 $N \cdot kg^{-1}$). Lastly, as a result of comparing the leaving phase to the propulsion-deceleration phase males and females both increased but the females to greater extent. For relative phase impulse patterns were also present. Cell means for the unweighted phase were relatively similar for males and females and increased when comparing the unweighted with net impulse, and acceleration-propulsion phases. However, males exhibited greater increases when comparing the unweighted (males: 1.29 ± 0.23 $Ns \cdot kg^{-1}$ vs. females: 1.23 ± 0.23 $Ns \cdot kg^{-1}$) to the net impulse (males: 2.73 ± 0.27 $Ns \cdot kg^{-1}$ vs. females: 2.35 ± 0.30 $Ns \cdot kg^{-1}$), and acceleration-propulsion phases (males: 2.90 ± 0.26 $Ns \cdot kg^{-1}$ vs. females: 2.52 ± 0.28 $Ns \cdot kg^{-1}$). Similarly, when comparing the stretching phase (males: 1.26 ± 0.23 $Ns \cdot kg^{-1}$ vs. females: 1.19 ± 0.22 $Ns \cdot kg^{-1}$) to the net impulse, and acceleration-propulsion phases, cell means increased with males again exhibiting a greater increase. Comparing the net impulse phase to the leaving (males: 0.15 ± 0.03 $Ns \cdot kg^{-1}$ vs. females: 0.16 ±

0.04 Ns·kg^{-1}), and propulsion-deceleration phases (males: 0.14 ± 0.03 Ns·kg^{-1} vs. females: 0.15 ± 0.04 Ns·kg^{-1}) resulted in both males and females decreasing to more similar values, but again considering the difference in the cell means for the net impulse phase, this decrease was to a greater extent in males.

Tables 3.3-3.5 display summaries of the phase by performance group simple interactions (two phases x two performance groups) found to be statistically significant including cell means and standard deviations. For relative magnitude, increasing trends in cell means were observed when comparing unweighted phase to the stretching, net impulse, acceleration-propulsion, and propulsion-deceleration phases with the higher performance groups exhibiting a greater magnitude of increase. Decreasing trends in the cell means were observed when comparing stretching to leaving and propulsion-deceleration phases, the net impulse phase to the leaving and propulsion-deceleration phases, and the acceleration-propulsion phase to the leaving phase, with the higher performance groups exhibiting a greater rate of decrease. For relative phase impulse examination of cell means revealed additional patterns between performance groups. For all groups similar increasing trends were observed when comparing the unweighted phase to the net impulse phase, and the stretching phase to the net impulse phase with the HPG exhibiting the greatest increase. Similar decreasing trends were observed when comparing the unweighted phase to the leaving and propulsion-deceleration phases, the stretching phase to the leaving and propulsion-deceleration phases, the net impulse phase to the leaving and propulsion-deceleration phases, and the acceleration-propulsion phase to the leaving and propulsion-deceleration phases with significant interactions present between all groups. Similar neutral trends were observed when comparing cell means of the net impulse phase and the acceleration-propulsion phase with the higher performance groups having the greater cell means. Additionally, neutral trends were present when comparing the leaving and propulsion-deceleration phases; however, in this comparison cell means were highest in the lower performance groups.

Table 3.3 Summary of Phase by Performance Group *Post Hoc* Interactions for Relative Magnitude

		Comparison	HPG	MPG	LPG
Relative Magnitude ($N \cdot kg^{-1}$)	*	UW	7.62 ± 1.28	-	5.92 ± 1.31
		STR	14.87 ± 2.85	-	10.52 ± 2.15
	*	UW	7.62 ± 1.28	-	5.92 ± 1.31
		NI	15.19 ± 2.32	-	11.41 ± 2.11
	*	UW	7.62 ± 1.28	-	5.92 ± 1.31
		AP	15.19 ± 2.32	-	11.41 ± 2.11
	*	UW	7.62 ± 1.28	-	5.92 ± 1.31
		PD	9.81 ± 0.06	-	9.77 ± 0.04
	* †	STR	14.87 ± 2.85	12.36 ± 2.46	10.52 ± 2.15
		LV	9.17 ± 0.83	9.14 ± 0.97	8.48 ± 0.97
	* †	STR	14.87 ± 2.85	12.36 ± 2.46	10.52 ± 2.15
		PD	9.81 ± 0.06	9.79 ± 0.07	9.77 ± 0.04
	* †	NI	15.19 ± 2.32	13.20 ± 2.25	11.41 ± 2.11
		LV	9.17 ± 0.83	9.14 ± 0.97	8.48 ± 0.97
	* †	NI	15.19 ± 2.32	13.20 ± 2.25	11.41 ± 2.11
		PD	9.81 ± 0.06	9.79 ± 0.07	9.77 ± 0.04
	* †	AP	15.19 ± 2.32	13.20 ± 2.25	11.41 ± 2.11
		LV	9.17 ± 0.83	9.14 ± 0.97	8.48 ± 0.97

Note: * indicates statistically significant interaction between the HP and LP group; † indicates statistically significant interaction between HP and MP groups, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

Table 3.4 Summary of Phase by Performance Group *Post Hoc* Interactions for Relative Impulse

		Comparison	HPG	MPG	LPG
	*	UW	1.45 ± 0.18	-	1.07 ± 0.16
		NI	2.85 ± 0.21	-	2.25 ± 0.29
	‡	UW	1.45 ± 0.18	1.27 ± 0.19	1.07 ± 0.16
		LV	0.14 ± 0.02	0.16 ± 0.03	0.18 ± 0.03
	‡	UW	1.45 ± 0.18	1.27 ± 0.19	1.07 ± 0.16
		PD	0.12 ± 0.02	0.15 ± 0.03	0.17 ± 0.03
	*	STR	1.41 ± 0.17	-	1.05 ± 0.15
		NI	2.85 ± 0.21	-	2.25 ± 0.29
	‡	STR	1.41 ± 0.17	1.22 ± 0.18	1.05 ± 0.15
		LV	0.14 ± 0.02	0.16 ± 0.03	0.18 ± 0.03
Relative Impulse ($Ns \cdot kg^{-1}$)	‡	STR	1.41 ± 0.17	1.22 ± 0.18	1.05 ± 0.15
		PD	0.12 ± 0.02	0.15 ± 0.03	0.17 ± 0.03
	* †	NI	2.85 ± 0.21	2.52 ± 0.22	2.25 ± 0.29
		AP	3.00 ± 0.21	2.68 ± 0.22	2.44 ± 0.28
	‡	NI	2.85 ± 0.21	2.52 ± 0.22	2.25 ± 0.29
		LV	0.14 ± 0.02	0.16 ± 0.03	0.18 ± 0.03
	‡	NI	2.85 ± 0.21	2.52 ± 0.22	2.25 ± 0.29
		PD	0.12 ± 0.02	0.15 ± 0.03	0.17 ± 0.03
	‡	AP	3.00 ± 0.21	2.68 ± 0.22	2.44 ± 0.28
		LV	0.14 ± 0.02	0.16 ± 0.03	0.18 ± 0.03
	‡	AP	3.00 ± 0.21	2.68 ± 0.22	2.44 ± 0.28
		PD	0.12 ± 0.02	0.15 ± 0.03	0.17 ± 0.03
	*	LV	0.14 ± 0.02	-	0.18 ± 0.03
		PD	0.12 ± 0.02	-	0.17 ± 0.03

Note: * indicates statistically significant interaction between the HP and LP group; † indicates statistically significant interaction between MPG and LPG group; ‡ indicates statistically significant interaction between all groups, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

Table 3.5 Summary of Phase by Performance Group *Post Hoc* Interactions for Shape Factor

		Comparison	HPG	MPG	LPG
Shape Factor (%)	*	STR	58.7 ± 8.9	-	52.9 ± 7.6
		LV	58.3 ± 1.9	-	61.0 ± 3.03

Note. * indicates statistically significant interaction between the HP and LP groups, UW = unweighted phase, STR = stretching phase, LV = leaving phase

For shape factor, *post hoc* simple interaction comparison revealed a clear disordinal pattern of the cell means in that HPG decreased shape factor from the stretching to the leaving phases while LPG showed the opposite trend (figure 3.2). Because of this interaction pattern further examination was conducted to investigate how a change in shape factor between the two phases is related to jumping performance. In order to do this, a ratio of stretching to the leaving phase shape factor was calculated. A one-way ANOVA found ratios to be statistically different between performance groups $F(2, 87) = 7.21$, $\eta^2 = .142$, $p = .001$. The mean ratio of stretching shape factor to leaving shape factor was 1.00 ± 0.16 for the HPG, 0.97 ± 0.15 for the MPG group and 0.87 ± 0.13 for the LPG. Additionally, a statistically significant linear trend ($p < .001$) was identified when comparing ratios between groups, indicating that as stretching to leaving shape factor ratio increased, so did JH in a linear fashion.

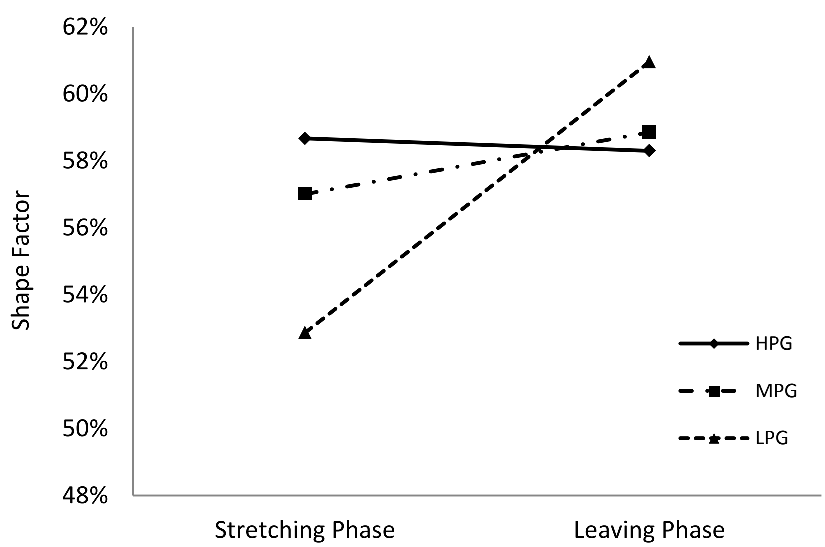

Figure 3.2 Plot of *post hoc* interaction effect for comparisons of shape factor between the stretching and leaving phases

Averaged phase comparisons

Comparisons of the average phase curves found several areas of non-overlap between 95% confidence limits. In the unweighted phase (figure 3.3A), a greater negative amplitude was observed in the HPG as compared to the LPG from 29.5% to 100% of the normalized phase, and the MPG was greater than the LPG from 18.1% to 31.0% and 74.5% to 100% of the phase. The 95% confidence limits overlapped during the entire phase of the HPG and MPG. Additionally, areas of non-overlap were not present when comparing the unweighted phase of males and female (figure 3.4A). In the stretching phase (figure 3.4B), the HPG was greater than the MPG from 70.0% to 100.0% of the phase. The MPG was greater than the LPG from 15.0% to 100%, and the HPG was greater than the LPG throughout the entire (0.0% to 100%) phase. There were no areas of non-overlap found between males and females in the stretching phase (figure 3.4B). For the net impulse phase (figure 3.3C) the HPG was greater than the MPG from 0.0% to 16.0% of the normalized phase. The MPG was greater than the LPG from 0.0% to 10.5%, and the HPG was greater than the LPG for the entire (0.0 % -100%) net impulse phase. Additionally, when comparing males and females, males were greater from 2.0% to 98.0% of the net impulse phase (figure 3.4C). Analysis of the leaving phase (figure 3.4E) found the MPG to be greater than the LPG from 0.0% to 47.0% of the phase, and the HPG to be greater than the LPG form 0.0% to 11.7% of the phase. There were no areas of non-overlap found between the HPG and the MPG or when comparing males and females (figure 3.4E). Finally, there were no areas of non-overlap found for any comparison (performance group or sex) for the propulsion-deceleration phase (Figures 3.3F and 3.4F).

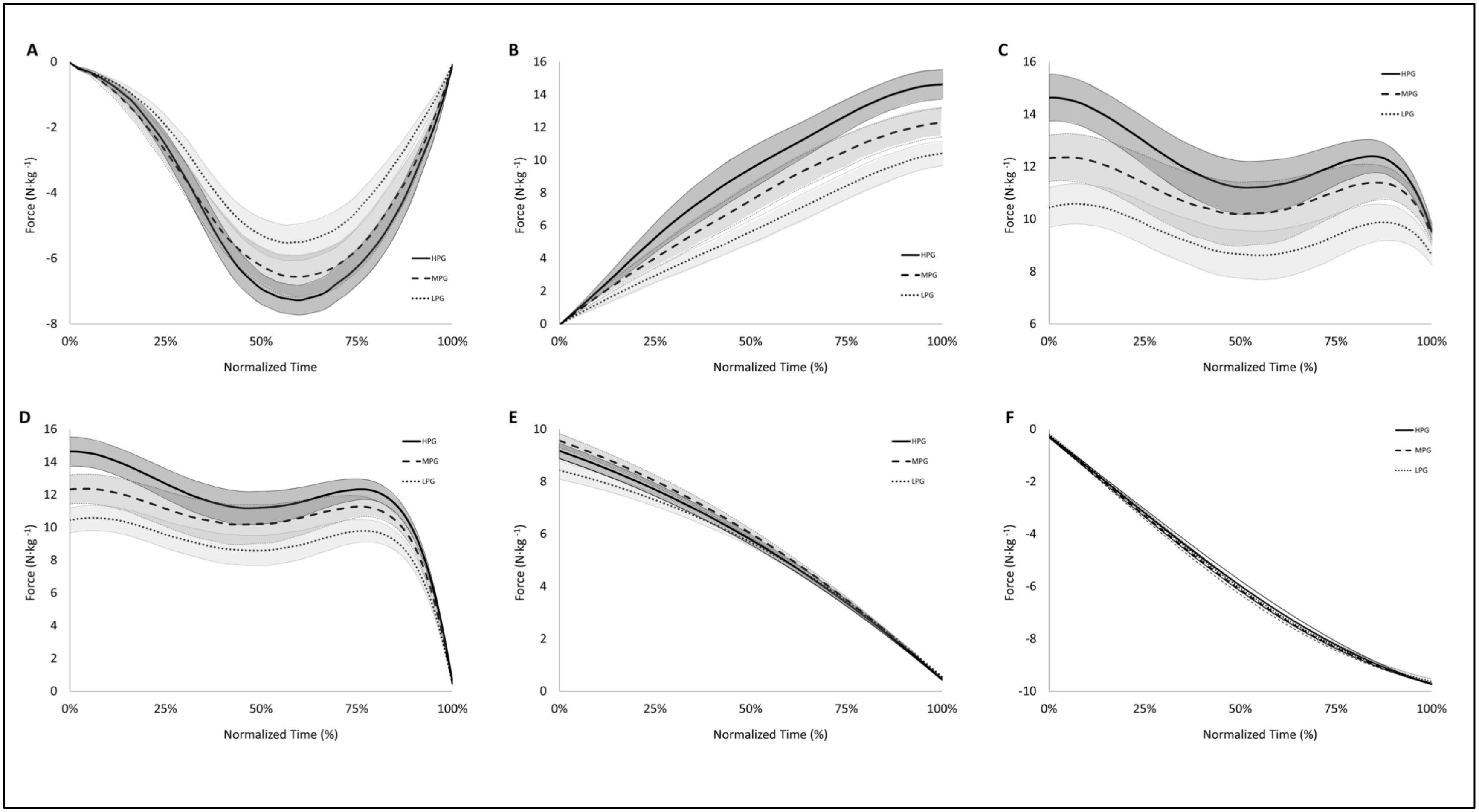

Figure 3.3 Normalized resampled CMJ F-t curve phases by performance group. A) unweighted phase, B) stretching phase, C) net impulse phase, D) acceleration-propulsion phase, E) leaving phase, and F) propulsion-deceleration phase. Shaded areas represent 95% upper and lower confidence limits for mean curves

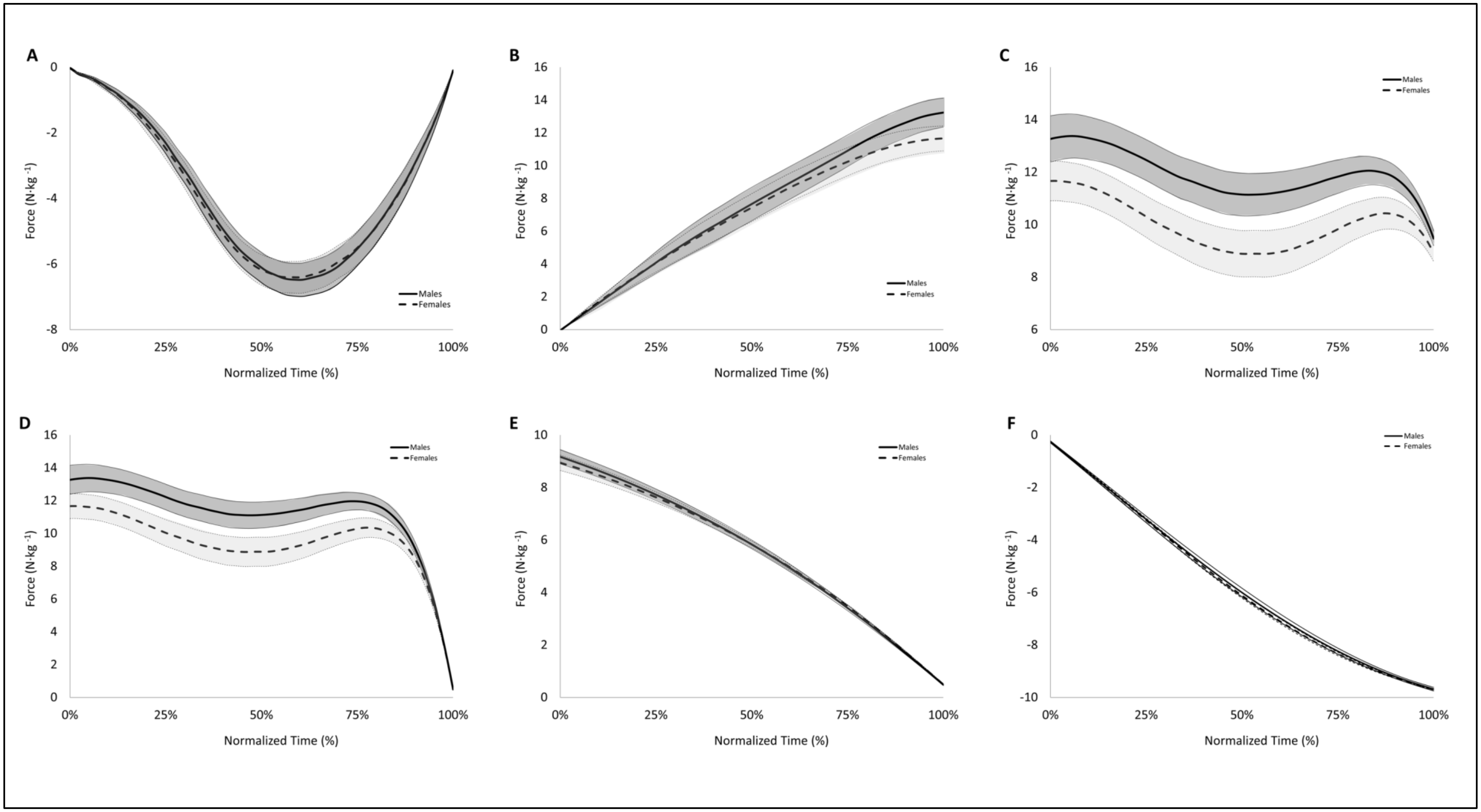

Figure 3.4 Normalized resampled CMJ F-t curve phases between male and female athletes. A) unweighted phase, B) stretching phase, C) net impulse phase, D) acceleration-propulsion phase, E) leaving phase, and F) propulsion-deceleration phase. Shaded areas represent 95% upper and lower confidence limits for the mean curves

Discussion

The purpose of the study was to examine phase characteristics of the CMJ F-t curve between jumpers of different abilities. The primary findings of the present study were: 1) the performance groups differed for relative phase magnitude primarily in the stretching, net impulse, and acceleration-propulsion phase, and for relative phase impulse in the unweighted, stretching, net impulse, and acceleration-propulsion phases, with highest jumpers achieving the greatest values, 2) males and females differed in relative phase magnitude and impulse with males exhibiting greater magnitudes in the stretching, net impulse, and acceleration-propulsion phases and greater relative impulse in the net impulse and acceleration-propulsion phases, 3) phase duration was found not to be statistically different between jumpers, 4) for shape factor, performance groups only differed when comparing the stretching and leaving phases, with the higher jumpers producing greater shape factors in the stretching phase.

Considering that statistical differences were identified in relative phase magnitude and impulse as well as shape factor between CMJ F-t curve phases of jumpers of different ability (i.e. JH), this study partially supports the suggestion that F-t curves could serve as diagnostic tools for monitoring and optimizing a movement [11, 15, 19]. Furthermore, the results of the present study identified key phase characteristics that may prove useful in identifying movement strategies or neuromuscular capacities to improve in order to increase jump height.

Previous research has identified relative impulse as a determining factor in vertical jump height [20, 27]. Additionally, maximizing the size (magnitude and area) of positive impulse (figure 3.1: points A-E) has been theorized to enhance jump performance [1]. The results of the present study are in agreement with the aforementioned work, in that better jumpers were associated with: 1) greater relative magnitudes throughout the positive impulse of the F-t curve (i.e.

stretching, net impulse, and acceleration-propulsion phases), and 2) greater relative impulse throughout the unweighted, stretching, net impulse, and acceleration-propulsion phases of the movement. These differences between phase characteristics can be observed when viewing the average phase curves of the CMJ (figure 3.3). In the unweighted phase, although the overall pattern of the phase is quite similar among groups, the negative amplitude (peak negative force) of the curves particularly between the HPG and LPG is notably different. Clear differences in averaged curves can also be seen for the remaining positive impulse phases particularly the latter portion of the stretching phase and early net impulse phase (figure 3.3B and C). In addition to a greater magnitude in these specific portions of the F-t curve, better jumpers also maintained a greater relative force throughout the net impulse/acceleration-propulsion phase, and consequently produced greater impulse. Moreover, it was in these areas of the F-t curve that the greatest separation was exhibited between the HPG and LPG average curves (figure 3.3C and D). Average curves for both the leaving and propulsion-deceleration phases were relatively similar for all comparisons suggesting these characteristics of these phases have little influence on jump height.

As illustrated by the comparison of average curves, jumpers capable of producing greater relative magnitudes (i.e. relative force) late in the stretching phase initiate the concentric/propulsive phase at a greater level of force and seem to maintain higher force throughout the propulsive phase contributing to a greater jump height. This observation is in agreement with previous research regarding the proposed contribution of the countermovement and eccentric phase to jump performance [2, 3]. Additionally, the stretching phase is speculated to reflect a jumpers ability to transition to the concentric action as well as the magnitude of the stretch experienced by the musculotendinous unit following the initial countermovement [19].

Therefore, the characteristics of this phase may provide information regarding an athlete's stretch-shortening cycle function as well as eccentric force production capacity. A pronounced magnitude during this phase (initial peak in the F-t curve) has been previously noted as characteristic of proficient jumpers [31]. Additionally, this feature of the F-t curve has been shown to appear following power-focused training [6]. Thus, the magnitude of the stretching phase or initial peak in the F-t curve may be a characteristic of interest in monitoring and jump analysis. However, future research is warranted to elucidate the exact mechanisms responsible for this characteristic as well its role in jump performance.

Interestingly the present study found that CMJ phase duration did not statistically differ between performance groups or male and female athletes. The finding regarding phase durations are similar between jumpers is in agreement with the recent findings of Laffaye, Wagner, Tombleson [22] reporting CMJ time-based variables alone were weak predictors of JH. Additionally, previous reports have noted similar jump durations between jumpers of different abilities [6] as well as training backgrounds [43]. When comparing males and females, individual phase durations were markedly similar, with the greatest mean difference (-24 ms) found in the unweighted phase (males: 365 ± 53 ms vs. females: 341± 54 ms). These similarities found in duration are in agreement with previous studies indicating the temporal structure of the CMJ F-t curve is comparable between males and females [22, 44]. The similarities in temporal structure of F-t curve phases suggest that phase duration plays a minor role in performance and other factors are responsible for improved JH.

Sex differences were noted for both relative phase magnitude as well as relative phase impulse. Specifically, males produced greater relative magnitudes during the stretching, net impulse, and acceleration-propulsion phases and greater relative impulse in the net impulse and acceleration-propulsion phases. In other words, the primary difference between males and females was related to both the rate and magnitude of relative force production during phases encompassing both peak eccentric and concentric force (figure 3.4B and C). This result is illustrated by the difference in the averaged curves when comparing males and females (figure 3.4 B, C, and D). Between males and females, the average curves for the unweighted and leaving and propulsion-deceleration phases were relatively similar. However, in the late stretching phase, as well as in the net impulse/acceleration-propulsion phases a shift in the shape of the curve can be seen resulting in areas of non-overlap existing for the majority (2.0% to 87.5%) of the normalized acceleration-propulsion phase. A similar pattern in the stretching and net impulse/acceleration-propulsion phases was exhibited by the HPG (figure 3.3B, C, and D). Based on this observation it is speculated that there may be a shared characteristic between both males and proficient jumpers influencing this characteristic of the F-t curve. The exact mechanism is presently unknown. However, previous research has demonstrated that in general males possess greater levels of relative strength as compared to female counterparts [30, 39]. The greater relative phase magnitudes and phase impulse found in the male athletes may be reflective of greater force production capacity likely influenced by characteristics of the neuromuscular system such as increased neural drive, percentage of type II muscle fibers. Thus, sex differences found in CMJ F-t curve phase characteristics may be in fact be strength differences.

The shape of the impulse produced during a phase (assessed through shape factor) was found to provide little information about JH. However, an unexpected finding of the present study was the disordinal interaction pattern (figure 3.2) produced when comparing shape factors between the stretching and leaving phases. This interaction pattern suggested that higher jumpers exhibit greater congruency in the relative shape of the impulse between the stretching and leaving phases. Calculation of the shape factor ratio suggested that higher jumpers (i.e. HPG) possess a stretching-to-leaving shape factor ratio of closer to 1.0, whereas lower jumpers (i.e. LPG) produce ratios of >1.0. Analysis of cell means (table 3.5) indicates that the primary factor influencing this ratio shift was the stretching shape factor, as the leaving shape factor was relatively similar between groups. This increased shape factor exhibited by the HPG could be related to the greater rise in force (i.e. eccentric rate of force development) visible when comparing the average curves of the stretching phase between groups (figure 3.3B). This finding suggests that more proficient jumpers not only produce a greater magnitude stretching phase with a greater area (impulse) as discussed above, additionally, the impulse becomes more rectangular in shape (i.e. occupies a greater portion of the rectangle drawn around the phase). Furthermore, the presence of a statistically significant linear trend between ratios of the performance groups suggests this variable may be linearly related to jump height. This finding supports the theory outlined by Adamson and Whitney [1] detailing how impulse may be optimized in regards to improving jump performance. Based on this result, identifying training methods or the neuromuscular capacities that would lead to an increased stretching shape factor may contribute to improved jump performance. However, further investigation of this variable's role in JH is necessary.

In conclusion, the present study was successful in identifying several CMJ F-t phase characteristics that differ between jumpers based on performance. It seems that relative magnitude of the stretching, net impulse, and acceleration propulsion phases as well as the relative impulse of the unweighted, stretching, net impulse, and acceleration-propulsion phases are primary characteristics influencing jump performance. Similar differences were exhibited between males and females and are perhaps the result of differences in relative strength and force production capacity. Interestingly, phase duration was similar between groups as well as between males and females suggesting this characteristic is of little importance to jump performance (JH). Finally, a potentially meaningful relationship was found when comparing the shape factors of the stretching and leaving phases with respect to JH. It should be noted that this study was the first of its kind by attempting a phase by phase analysis of F-t characteristics. Consequently, additional research is warranted to support these findings. From a practical standpoint, the results of this investigation may suggest the following regarding jump performance (JH): 1) training methods to increase JH may be most effective if focused on maximizing vertical force production characteristics in order to influence relative magnitude and impulse, 2) characteristics of the stretching phase (magnitude and shape), both in isolation and in relation to other phases may prove to be an valuable aspect of the CMJ F-t curve for monitoring an athlete's explosive state.

References

1. Adamson GT, Whitney RJ. Critical appraisal of jumping as measure of human power. *In Vredenbregt, J. (ed.), Biomechanics II, Baltimore, Md., University Park Press, p.208-211.*; 1971.
2. Bobbert MF, Casius LJ. Is the effect of a countermovement on jump height due to active state development? *Medicine & Science in Sports & Exercise.* 2005;37(3):440-446.
3. Bobbert MF, Gerritsen KG, Litjens MC, Van Soest AJ. Why is countermovement jump height greater than squat jump height? *Medicine & Science in Sports & Exercise.* 1996;28:1402-1412.
4. Carlock JM, Smith SL, Hartman MJ, et al. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *The Journal of Strength & Conditioning Research.* 2004;18(3):534-539.
5. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *Journal of Applied Biomechanics.* 2008;24(2):112.
6. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength & Conditioning Research.* 2009;23(1):177-186.
7. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Medicine & Science in Sports & Exercise.* 2010;42(8):1582-1598.

8. Cormie P, McGuigan MR, Newton RU. Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sports & Exercise.* 2010;42(9):1731-1744.
9. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine & Science in Sports & Exercise.* 2010;42(8):1566-1581.
10. Desipres M. Polyparametric study of the vertical jump. *In, Komi, P.V. (ed.), Biomechanics V-B, Baltimore, Md., University Park Press, 1976, p. 73-80.*; 1976.
11. Dowling JJ, Vamos L. Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics.* 1993;9:95-95.
12. Garhammer J, Gregor R. Propulsion forces as a function of intensity for weightlifting and vertical jumping. *The Journal of Strength & Conditioning Research.* 1992;6(3):129-134.
13. Gathercole RJ, Sporer BC, Stellingwerff T, Sleivert G. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology & Performance.* 2015;10(1):84-92.
14. Henry FM. “Best” versus “average” individual scores. *Research Quarterly. American Association for Health Physical Education and Recreation.* 1967;38(2):317-320.
15. Hochmuth G. *Biomechanics of athletic movement*. Berlin: Sportverlag; 1984.
16. Holm S. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics.* 1979:65-70.
17. Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Medicine.* 2000;30(1):1-15.

18. Hunebelle G, Damoiseau J. Medicine and Sport, vol. 8: Biomechanics III, pp. 417-425 (Karger, Basel 1973). *Biomechanics III.* 1973;3:417.

19. Kibele A. Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics.* 1998;14:105-117.

20. Kirby TJ, McBride JM, Haines TL, Dayne AM. Relative net vertical impulse determines jumping performance. *Journal of Applied Bbiomechanics.* 2011;27(3):207-214.

21. Kraska JM, Ramsey MW, Haff GG, et al. Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology & Performance.* 2009;4(4):461-473.

22. Laffaye G, Wagner PP, Tombleson TIL. Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables. *The Journal of Strength & Conditioning Research.* 2014;28(4):1096-1105.

23. Lees A, Vanrenterghem J, Clercq DD. Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics.* 2004;37(12):1929-1940.

24. Levine TR, Hullett CR. Eta Squared, Partial Eta Squared, and Misreporting of Effect Size in Communication Research. *Human Communication Research.* 2002;28(4):612-625.

25. Linthorne N. Analysis of standing vertical jumps using a force platform. *American Journal of Physics.* 2001;69:1198.

26. Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and factorial validity of squat and countermovement jump tests. *The Journal of Strength & Conditioning Research.* 2004;18(3):551-555.

27. McBride JM, Kirby TJ, Haines TL, Skinner J. Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with

various loads. *International Journal of Sports Physiology & Performance.* 2010;5(4):484-496.

28. McBride JM, Triplett-McBride T, Davie A, Newton RU. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *The Journal of Strength & Conditioning Research.* 1999;13(1):58-66.

29. McMaster D, Gill N, Cronin J, McGuigan M. A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine.* 2014;44(5):603-623.

30. Miller AEJ, MacDougall JD, Tarnopolsky MA, Sale DG. Gender differences in strength and muscle fiber characteristics. *European Journal of Applied Physiology and Occupational Physiology.* 1993;66(3):254-262.

31. Miller DI, East DJ. Kinematic and kinetic correlates of vertical jumping in women. *In Biomechanics v-B, Baltimore, University Park Press., 1976, p.65-72.*; 1976.

32. Mizuguchi S. Net Impulse and Net Impulse Characteristics in Vertical Jumping (Doctoral dissertation). *East Tennessee State University, Johnson City, TN.* 2012.

33. Moir GL, Button C, Glaister M, Stone MH. Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *The Journal of Strength & Conditioning Research.* 2004;18(2):276-280.

34. Moir GL, Garcia A, Dwyer G. Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology & Performance.* 2009;4(3):317.

35. Moir GL, Sanders R, Button C, Glaister M. The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *The Journal of Strength & Conditioning Research.* 2005;19(1):140-145.

36. Psycharakis SG, Miller S. Estimation of errors in force platform data. *Research Quarterly for Exercise & Sport.* 2006;77(4):514-518.

37. Richter C, O'Connor NE, Marshall B, Moran K. Analysis of characterizing phases on waveform: an application to vertical jumps. *Journal of Applied Biomechanics.* 2014;30(2):316-321.

38. Stone MH, O'Bryant H, McCoy L, Coglianese R, Lehmkuhl M, Schilling B. Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps. *The Journal of Strength & Conditioning Research.* 2003;17(1):140-147.

39. Stone MH, Sands WA, Pierce KC, Carlock J, Cardinale M, Newton RU. Relationship of maximum strength to weightlifting performance. *Medicine & Science in Sports & Exercise.* 2005;37(6):1037-1043.

40. Street G, McMillan S, Board W, Rasmussen M, Heneghan JM. Sources of Error in Determining Countermovement Jump Height With the Impulse Method. *Journal of Applied Biomechanics.* 2001;17:43-54.

41. Tabachnick BG, Fidell LS. *Experimental designs using ANOVA*: Thomson/Brooks/Cole; 2007.

42. Taylor KL, Chapman DW, Cronin JB, Newton MJ, Gill ND. Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning.* 2012;20(1):12-23.

43. Ugrinowitsch C, Tricoli V, Rodacki AL, Batista M, Ricard MD. Influence of training background on jumping height. *The Journal of Strength & Conditioning Research.* 2007;21(3):848-852.

44. Vaverka F, Janura M. Comparison of the force-time structure of the vertical jump between men and women. *In proceedings of: XV Congress of the International Society of Biomechanics in Sports.* 1997.

45. Winter DA, Sidwall HG, Hobson DA. Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics.* 1974;7(2):157-159.

46. Yu B. Determination of the appropriate cutoff frequency in the digital filter data smoothing procedure (Master's thesis) *Kansas State University, Manhattan, KS.* 1998.

47. Yu B, Gabriel D, Noble L, An K-N. Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *Journal of Applied Biomechanics.* 1999;15:318-329.

CHAPTER 4

THE INFLUENCE OF MAXIMAL ISOMETRIC STRENGTH ON COUNTERMOVEMENT JUMP FORCE-TIME CURVE PHASE CHARACTERISTICS IN ATHLETES

Authors: [1]Christopher J. Sole, [1]Satoshi Mizuguchi, [1]Kimitake Sato, [2]Gavin L. Moir, and [1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Exercise Science, East Stroudsburg University of Pennsylvania, East Stroudsburg, PA, USA

ABSTRACT

Purpose: To compare the phase characteristics of the countermovement jump (CMJ) force-time (F-t) curve between athletes based on maximal isometric strength. ***Methods:*** On the basis of allometrically scaled isometric peak force (IPFa), the top, middle, and lower twenty male and twenty female athletes were selected for analysis from a sample of 144 athletes. Additionally, athletes were grouped by jump height within strength performance groups to form jump performance sub-groups. Athletes CMJ F-t curves were analyzed and the following phase characteristics were determined: duration, magnitude, area (impulse), and shape. A series of 3-way mixed ANOVAs were used to examine the differences in F-t curve phase characteristics between strength groups in males and females. ***Results:*** Statistically significant phase by strength and phase by jump sub-group effects were found. *Post hoc* analyses for the phase by strength effect indicated that athletes with the greatest IPFa exhibited shorter unweighted phase durations. *Post hoc* analyses for the phase by jump subgroup indicated proficient jumpers exhibited greater phase magnitude and impulse throughout the phases of the CMJ F-t curve positive impulse. Additionally, more proficient jumpers are associated with a greater shape factor in the stretching phase of the CMJ F-t curve. ***Conclusion:*** The results of this analysis suggest stronger athletes exhibit shorter unweighted phase durations as compared to less-strong athletes. Additionally, the CMJ F-t curve phase characteristics common among proficient jumpers exist irrespective of maximal isometric strength.

Keywords: Countermovement jump, strength, force-time curve, force platform, shape factor

Introduction

The countermovement jump (CMJ) is a commonly used assessment in sport science and athlete performance monitoring [55]. Many performance measures of CMJ have been found to be reliable, require minimal familiarization, and be relatively non-invasive and non-fatiguing[33, 40-43]. Due to the practical nature of this measurement, it has been suggested that CMJ can be performed regularly throughout a training process as a simple and effective method of monitoring an athlete's performance state [2, 3, 16-18, 39, 49].

The criterion performance variable for CMJ testing is commonly jump height (JH). However, there exists a multitude of kinetic and kinematic variables regularly calculated during CMJ assessment [32]. As a commonly used test in sport science and strength and conditioning research, a large body of empirical literature documented the effect of training (e.g. strength- and explosive-type training) on CMJ performance variables. The majority of research deals with peak and average variables such as peak and average force, velocity, and power. Although useful in quantifying kinetic and kinematic characteristics of the movement, it has been suggested by several authors that these variables are limited in their ability to elucidate exact underlying mechanisms of performance and/or adaptation[10-13, 47]. Considering this potential limitation of common CMJ performance variables, recent research involving CMJ has focused on alternative analyses including evaluations of the entire CMJ force-time (F-t) curve [9-13], or through using alternative variables related to timing of specific aspects of the movement mechanics (e.g. the eccentric phase) [17]. Although these forms of analysis are promising for the delineation of mechanistic changes in CMJ performance in response to training, in many cases they include variables that characterize the entire F-t curve and/or include multiple phases of the curve. Perhaps a more appropriate first step in a mechanistic analysis of CMJ performance may be through assessing the curve on a phase-by-phase basis, through the characterization (size, duration, area, and shape) of each individual phase of the CMJ F-t curve.

In our previous investigation [48] we reported that a phase-by-phase analysis of the CMJ F-t curve was effective in identifying key CMJ F-t curve phase characteristics exhibited by proficient jumpers as compared to less-proficient jumpers. Briefly, proficient jumpers were associated with greater relative phase magnitudes throughout phases contained within the positive impulse of the CMJ F-t curve, as well as greater relative impulse throughout phases composing both the eccentric and concentric portions of the jump. Additionally, despite the lack of a sex difference in phase duration and shape, male jumpers exhibited greater relative phase magnitude and impulse and greater JHs as compared to females. It is illogical to assume males are simply technically better jumpers, thus other factors such as force production capacity (i.e. strength) may be underpinning these observed differences between male and females jumpers.

The isometric mid-thigh pull (IMTP) is a commonly used measure of strength and explosiveness in athlete performance testing and research[21, 22, 26, 28]. This test has been effectively implemented as an assessment of strength and explosiveness in multiple athletes from multiple sporting disciplines [21, 22, 25, 26, 28, 35, 36, 44, 51, 52]. Performance in the IMTP is often quantified using the peak ground reaction force obtained during this test, often reported as isometric peak force (IPF). Previous research has demonstrated strong relationships between IPF and several measures of lower-body dynamic strength and performance including CMJ performance variables such as jump height, peak force and peak power [26, 28, 44, 51, 52, 56].

Considering the relationship between CMJ performance variables such as JH and measures of isometric strength (IMTP) as well as JH and CMJ F-t curve characteristics, it is likely that an athlete's maximal force production capacity may be reflected in these same CMJ F-t curve phase characteristics. Establishing a relationship between a jumper's strength level and CMJ F-t phase characteristics may provide practitioners with an effective method indirectly assessing athlete strength through analysis of the CMJ F-t curve itself. However, to date only information regarding the influence of jumping ability on these specific phase characteristics (size, duration, area, and shape) exist, and it is currently unknown precisely how an athlete's strength level may influence CMJ F-t curve phase characteristics. Thus, the purpose of this study was to compare phase characteristics of athlete's countermovement jump force-time curve based on maximal isometric strength.

Methods

Participants

Data from 144 athletes (age = 20.3 ± 1.3 y, body mass = 75.1 ± 13.5 kg, height = 175.5 ± 10.1 cm; male, n = 72, age = 20.5 ± 1.5 y, body mass = 82.4 ± 11.4 kg, height = 182.4 ± 7.8 cm; female, n = 72, age = 20.1 ± 1.0 y, body mass = 67.8 ± 11.4 kg, height = 168.6 ± 7.0 cm) were included in the present study. All athletes were National Collegiate Athletic Association (NCAA) Division I level, competitive in a variety of sports (Table 4.1). All athletes' data were previously collected as part of an ongoing athlete performance monitoring program. The data included in the present study were approved by the East Tennessee State University Institutional Review Board.

Table 4.1 Athlete Demographic Information

	Sport	n	Age (y)	Body Mass (kg)	Height (cm)
Males	Baseball	22	20.2 ± 1.3	83.7 ± 7.4	180.6 ± 4.9
	Basketball	11	20.8 ± 1.3	89.9 ± 11.1	189.6 ± 4.9
	Soccer	22	21.0 ± 1.6	78.5 ± 9.1	180.1 ± 6.7
	Tennis	6	20.6 ± 1.8	76.7 ± 14.8	179.0 ± 13.8
	Track and Field				
	Jumps	7	20.3 ± 1.8	79.0 ± 9.2	182.1 ± 5.6
	Throws	2	19.8 ± 0.6	106.0 ± 26.9	194.0 ± 4.2
	Multi-Event	2	19.4 ± 1.4	77.1 ± 5.6	183.0 ± 9.9
Females	Soccer	22	20.0 ± 0.9	66.6 ± 9.4	167.6 ± 4.9
	Softball	21	20.6 ± 1.0	69.1 ± 8.5	167.0 ± 6.7
	Volleyball	19	19.7 ± 0.8	68.8 ± 8.4	173.0 ± 7.4
	Track and Field				
	Jumps	5	20.3 ± 1.6	60.4 ± 3.9	166.2 ± 7.7
	Throws	2	19.7 ± 0.4	100.6 ± 43.3	174.5 ± 3.5
	Sprints	3	20.9 ± 1.3	60.1 ± 6.1	166.3 ± 10.1

Note: Values are means ± standard deviations

Study design

To investigate the influence of maximal isometric force production capacity on CMJ F-t curve phase characteristics, athletes were first grouped based on allometrically scaled [52] peak isometric force (IPFa), obtained during isometric mid-thigh pull (IMTP) testing. Based on IPFa scores male and female athletes were independently ranked in ascending order. Once ranked, the top, middle, and lower 20 athletes were selected to form high (HPG_S), middle (MPG_S), and low (LPG_S) strength performance groups. Additionally, within each strength performance group jumpers were again ranked by jumping ability (criterion measure JH), to form high (HPG_J) and low (LPG_J) jump performance sub-groups. Table 4.2 displays mean and standard deviation for strength performance groups for both male and female athletes. A one-way analysis of variance (ANOVA) found performance groups to be statistically different between strength performance groups and between JH sub-groups (for both males and female athletes (males, IPFa ($F(2,57) = 130$, $\eta^2 = 0.820$, $p < 0.001$, jump height, $F(1,58) = 112$, $\eta^2 = 0.660$, $p < 0.001$); females, IPFa ($F(2,57) = 131$, $\eta^2 = 0.821$, $p < 0.001$, jump height, $F(1,58) = 97.3$, $\eta^2 = 0.626$, $p < 0.001$). In other words, athletes IPFa values were statistically different between strength performance groups for both male and females.

Table 4.2 Strength Performance Groups and Allometrically Scaled IPF

	Group	**IPFa ($N \cdot kg^{0.67}$)**
Males	HPG_s	260.62 ± 22.10
	MPG_s	219.39 ± 10.79
	LPG_s	178.12 ± 20.48
Females	HPG_s	163.61 ± 29.8
	MPG_s	114.39 ± 17.92
	LPG_s	69.11 ± 16.79

Note: Values are means ± standard deviations HPG_s = high strength performance group, MPG_s = mid strength performance group, LPG_s = low strength performance group, IPFa = allometrically scaled isometric peak force

Countermovement jump testing

Prior to all data collection athletes performed a standardized general warm-up routine consisting of 20 jumping-jacks and four sets of dynamic mid-thigh pulls (one set of five with a 20 kg Olympic barbell, followed by three sets of five with a barbell totaling 40 kg for females and 60 kg for males) [28]. Countermovement jump testing consisted of two submaximal jumps (50% and 75% of the athlete's maximum effort) and two maximal effort CMJs separated by approximately 60 seconds. In order to eliminate any contributions of an arm swing to jump performance [30] athletes performed all jumps while holding a nearly weightless (< 1 kg) plastic bar behind the neck, as described by previous authors [7, 28, 34, 50]. All jumps were performed on a uniaxial force platform (91 cm x 91 cm, Rice Lake Weighing Systems, Rice Lake, WI, USA) imbedded into the laboratory floor.

Isometric strength testing

Isometric mid-thigh pull testing immediately followed CMJ testing. Testing procedures including pulling apparatus and standardized pulling position were based on previously published research[22, 28]. Athletes were placed in a custom-built rack atop a force platform (91.0 cm x 91.0 cm, Rice Lake Weighing Systems, Rice Lake, WI, USA). The pulling apparatus (figure 4.1) was equipped with an adjustable bar that could be raised or lowered and locked into place. All trials were performed in a standardized pulling position consisting of a knee angle of 125 ± 5 degrees and hip angle of 145 ± 5 degrees [28] verified using a hand-held goniometer. To ensure grip strength was not a limiting factor, athlete's hands were fixed to bar using nylon weightlifting straps and athletic tape. Athletes were allowed two warm-up pulls (perceived 50 % and 75% of maximal effort) separated by approximately 45 seconds. Following the warm-up trials a minimum of two maximal efforts trials were performed by each athlete separated by approximately 120 seconds. Three or more trials were performed if an athlete's isometric peak force recorded during the first two trials differed by 200 N.

Figure 4.1 The isometric mid-thigh pull (IMTP) testing apparatus

During CMJ and IMTP data collection the force platform was interfaced with a PC using an analog-to-analog BNC interface box (BNC-2110), and 16-bit analog-to-digital board (NI PCI-6035E, National Instruments, Austin, TX, USA). All data were collected using custom designed programs (LabVIEW version 12.0, National Instruments, Austin, TX, USA). Voltage data from the force platform were collected at a sampling frequency of 1000 Hz [38, 53]. To minimize measurement error associated with force platform, all laboratory force platforms were regularly calibrated and maintained [45].

Data analysis

All data analyses were performed using custom designed programs (LabVIEW version 12.0, National Instruments, Austin, TX, USA). Force platform voltage data obtained during testing were converted to vertical ground reaction force using regression equations from laboratory calibrations and force-time curves were constructed. To reduce random noise, all ground reaction force data were processed using a fourth-order low-pass Butterworth digital filter [58] with an estimated optimum cutoff frequency of 40 Hz [60].

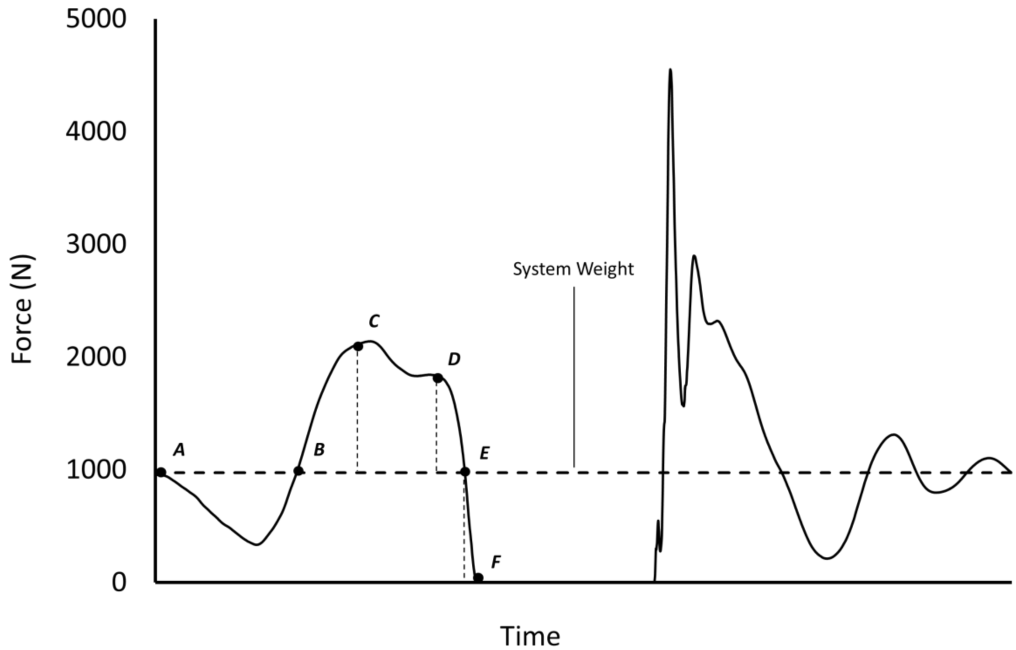

Figure 4.2 The CMJ F-t curve phases. Points A to B: unweighted phase, points B to C: stretching phase, points C to D: net impulse phase, points C to E: acceleration-propulsion phase, points D to E: leaving phase, points E to F: propulsion-deceleration phase

From the CMJ F-t curve, the following F-t curve phases (figure 4.2) were determined based on previous research [27, 32, 39, 57]: the unweighted phase, the stretching phase, the net impulse phase, the acceleration-propulsion phase, the leaving phase, and the propulsion-deceleration phase. The following variables were calculated for each phase of the CMJ F-t normalized (vertical ground reaction force minus system weight) curve (figure 4.2): 1) phase duration, calculated as the length of the phase in milliseconds, 2) relative phase magnitude, calculated as the height of the phase scaled to the system mass of the jumper, expressed as newtons per kg ($N \cdot kg^{-1}$) 3) relative phase impulse, calculated through integration of the phase F-t curve scaled to the system mass of the jumper and expressed in newton-seconds per kg ($Ns \cdot kg^{-1}$) , and 4) shape factor, calculated as a ratio of phase impulse relative to a rectangular shape formed around the impulse, expressed as a percentage [14, 39, 48]. To assess test-retest reliability, intraclass correlation coefficients (ICC) were calculated for each variable of interest. Random error was assessed using typical error expressed as a coefficient of variation (CV) [24]. ICC and CV values for all variables are displayed in table 4.3.

To perform a visual comparison of CMJ F-t curve phases, a computer resampling technique was employed similar to previous studies[9-13]. Briefly, CMJ F-t phase curves were reduced to an equal number of samples by adjusting the time delta between samples and resampling the curve. With each curve containing an equal number of samples, curves were normalized to time so that they could be compared between performance groups. Following the normalization technique the mean sampling frequencies for all curves was 634 ± 117 Hz.

Table 4.3 Test Re-test Reliability Statistics for F-t Curve Phase Characteristics

		CV%	ICC	95% CL
Duration	UW_{dur}	6.9	0.817	[0.734, 0.875]
	STR_{dur}	7.6	0.891	[0.839, 0.927]
	NI_{dur}	5.0	0.908	[0.863, 0.938]
	AP_{dur}	4.5	0.914	[0.872, 0.942]
	LV_{dur}	5.4	0.944	[0.916, 0.963]
	PD_{dur}	5.3	0.931	[0.897, 0.954]
Magnitude	UW_{mag}	9.8	0.909	[0.866, 0.939]
	STR_{mag}	6.2	0.960	[0.940, 0.973]
	NI_{mag}	5.2	0.963	[0.945, 0.976]
	AP_{mag}	5.2	0.963	[0.872, 0.942]
	LV_{mag}	4.0	0.968	[0.916, 0.963]
	PD_{mag}	1.0	0.997	[0.897,0.954]
Impulse	UW_{j}	5.7	0.956	[0.934, 0.971]
	STR_{j}	6.2	0.957	[0.935, 0.971]
	NI_{j}	2.1	0.993	[0.989, 0.995]
	AP_{j}	1.9	0.994	[0.994, 0.991]
	LV_{j}	8.1	0.956	[0.956, 0.933]
	PD_{j}	7.5	0.966	[0.966, 0.948]
Shape Factor	UW_{sf}	6.6	0.735	[0.593, 0.778]
	STR_{sf}	6.7	0.833	[0.756, 0.887]
	NI_{sf}	3.4	0.908	[0.864, 0.939]
	AP_{sf}	3.4	0.899	[0.850, 0.932]
	LV_{sf}	2.2	0.795	[0.705, 0.860]
	PD_{sf}	2.9	0.756	[0.652 0.832]

Note: UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase, JH = jump height, $_{dur}$ = duration, $_{mag}$ = magnitude, $_{j}$ = impulse, $_{sf}$ = shape factor. CV = typical error expressed as a coefficient of variation, ICC = intraclass correlation coefficient, 95% CL = 95% confidence limits

Statistical analyses

Four three-way mixed ANOVAs (three strength performance groups by two jump height performance groups by six phases) were used to determine statistically significant differences between levels of the independent variables. Effect size estimates for main and interaction effects were calculated using eta squared (η^2) [31]. Simple *post hoc* interaction tests were performed when necessary with the experimental type I error rate controlled using the Scheffe's adjusted critical *F* value [54]. All statistical analyses were performed using Statistical Package for Social Sciences (IBM SPSS Statistics for Windows, Version 22.0, IBM Corp., Armonk, NY). Statistical significance for all analyses was set at $p \leq 0.05$. Holm's simple sequential rejective test [23] was used to adjust the critical p value from $p \leq 0.05$ in order to further control for type I error associated with the multiple three-way mixed ANOVAs.

Results

Results of the three-way mixed ANOVAs for male and female athletes are displayed in tables 4.4 and 4.5, respectively. There was a statistically significant main effect for all phase characteristics (duration, relative magnitude, relative impulse, and shape factor), for both male and female athletes. For males, a statistically significant phase by strength interaction effect was found for phase duration. No statistically significant phase by strength interactions were found for female athletes for any variable. Statistically significant phase by jump performance interaction effects were found for both male and female athletes for relative phase impulse and relative phase magnitude. A statistically significant phase by jump performance interaction for shape factor was found in the analysis of female athletes. There were no phase by strength by jump performance three-way interactions found for any variables for males or females athletes.

Additionally, statistically significant jump performance group between subjects effects were found for relative magnitude and relative impulse for both male (relative magnitude: $F(1,54) = 16.5$, $\eta^2 = 0.036$, $p < 0.001$, relative impulse: $F(1,54) = 59$, $\eta^2 = 0.006$, $p < 0.001$) and female (relative magnitude: $F(1,54) = 14.8$, $\eta^2 = 0.047$, $p < 0.001$, relative impulse: $F(1,54) = 60$, $\eta^2 = 0.011$, $p < 0.001$) athletes.

Table 4.4 ANOVA Results for Analysis of Male Athletes

Effect	Characteristic	*df*	*F*	η^2	*p*
Phase	Duration	2.32, 125	1657	0.939	< 0.001
	Magnitude	1.66, 89.7	312	0.679	< 0.001
	Impulse	1.78, 96.2	5773	0.973	< 0.001
	Shape Factor	2.26, 122	282	0.781	< 0.001
Phase by Strength	Duration	4.46, 125	3.27	0.003	0.010
	Magnitude	3.32, 89.7	1.29	0.006	0.280
	Impulse	3.56, 96.2	0.66	0.001	0.614
	Shape Factor	4.53, 122	0.33	0.002	0.878
Phase by Jump Performance	Duration	3.32,122	0.99	0.001	0.386
	Magnitude	1.66, 89.7	11.7	0.025	< 0.001
	Impulse	1.78, 96.2	30.3	0.005	< 0.001
	Shape Factor	2.26, 122	1.83	0.005	0.159
Phase by Strength by Jump Performance	Duration	4.46, 125	0.65	0.001	0.650
	Magnitude	3.32, 89.7	2.32	0.010	0.074
	Impulse	3.56, 96.2	2.38	0.001	0.064
	Shape Factor	4.53, 122	1.53	0.008	0.189

Table 4.5 ANOVA Results for Analysis of Female Athletes

Effect	Characteristic	*df*	*F*	η^2	*p*
Phase	Duration	2.52, 136	1280	0.922	< 0.001
	Magnitude	2.09, 112	194	0.580	< 0.001
	Impulse	2.00, 108	3972	0.953	< 0.001
	Shape Factor	2.06, 111	221	0.729	< 0.001
Phase by Strength	Duration	5.05, 136	0.71	0.001	0.617
	Magnitude	4.17, 112	1.22	0.007	0.306
	Impulse	4.00, 108	2.87	0.001	0.026*
	Shape Factor	4.13, 111	1.29	0.008	0.279
Phase by Jump Performance	Duration	2.52, 136	1.24	0.001	0.295
	Magnitude	2.08, 112	4.98	0.015	0.008
	Impulse	2.00, 108	36.3	0.009	< 0.001
	Shape Factor	2.06, 111	3.32	0.008	0.042
Phase by Strength by Jump Performance	Duration	5.05, 136	0.90	0.001	0.478
	Magnitude	4.17, 112	0.72	0.004	0.585
	Impulse	4.00, 108	1.46	0.007	0.212
	Shape Factor	4.13, 111	0.86	0.006	0.493

Note: * indicated result was determined not statistically significant following Scheffe's adjustment

For the male athletes, simple *post hoc* interaction comparisons for the duration phase by strength interaction found statistically significant effects present between the HPG_S and MPG_S, and LPG_S when comparing durations of the unweighted phase to the net impulse and acceleration-propulsion phase durations (table 4.6). Specifically, the HPG_S (i.e. greatest IPFa) exhibited shorter unweighted phase durations as compared to both the MPG_S, and LPG_S.

Table 4.6 Summary of Statistically Significant Post Hoc Interactions for Phase Duration for the Phase by Strength Interaction for Male Athletes

		Comparison	HPG_s	MPG_s	LPG_S
Duration (ms)	*	UW	331.8 ± 36.1	372.6 ± 44.8	372.9 ± 61.1
		STR	183.4 ± 37.2	178.5 ± 28.2	174.9 ± 31.5
	*	UW	331.8 ± 36.1	372.6 ± 44.8	372.9 ± 61.1
		NI	236.9 ± 37.4	236.2 ± 27.9	232.4 ± 31.1
	*	UW	331.8 ± 36.1	372.6 ± 44.8	372.9 ± 61.1
		AP	264.7 ± 36.9	264.7 ± 29.9	261.4 ± 32.6

Note: * indicates statistically significant interaction between the HPG_S and MPG_S and LPG_S group. Note: UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, values are means ± standard deviations

For the phase by jump performance interaction simple *post hoc* interaction comparisons were also performed. A summary of all interactions found to be statistically significant are displayed in tables 4.7 and 4.8. When examining the plotted means for relative magnitude, common patterns were observed between proficient jumpers (HPG_J) and less-proficient jumpers (LPG_J). Positive trends were observed when comparing the means of the unweighted phase to the stretching, net impulse, and acceleration-propulsion phases. In both groups, mean values for the unweighted phase were relatively similar and increased when transitioning to the stretching, net impulse and acceleration-propulsion phases; with the HPG_J exhibiting the greatest increase in all comparisons. Negative trends were observed when comparing means of the stretching, net impulse, acceleration-propulsion phases to the leaving and propulsion-deceleration phases, with the HPG_J decreasing to a greater extent as both groups exhibited more similar means in the leaving and propulsion-deceleration phases. For relative phase impulse, patterns were also observed in cell mean trends for the male athletes. Positive trends were observed when comparing the unweighted phase to the net impulse phase as well as the stretching phase to the net impulse, and acceleration-propulsion phases. In all comparisons the HPG_J exhibited a greater increase, as cell means were similar in the unweighted and stretching phases between groups and greater discrepancies were observed between groups in the net impulse and acceleration phases. Similar negative trends were observed when comparing cell means of the unweighted phase to the leaving and propulsion-deceleration phases, the stretching phase to the leaving and propulsion-deceleration phases, the net impulse phase to the leaving and propulsion-deceleration phases and the acceleration-propulsion phase to the leaving and propulsion-deceleration phases. In all comparisons, the greatest means were observed in the HPG_J for the unweighted, stretching net impulse, and acceleration phases, with the HPG_J consequently exhibiting a greater decrease as cell means for both groups were similar for the leaving and propulsion-deceleration phases. In both comparisons the two performance groups exhibited similar means between phase with the HPG_J having the greatest relative impulse in the net-impulse and acceleration-propulsion phases, and the LPG_J exhibiting greater mean relative impulse in the leaving and propulsion-deceleration phases.

Table 4.7 Summary of Statistically Significant Post Hoc Interactions for Phase Magnitude for the Phase by Jump Performance Interaction for Male Athletes

	Comparison	HPG_J	LPG_J
Relative Magnitude ($N \cdot kg^{-1}$)	UW	7.35 ± 1.26	6.75 ± 1.50
	STR	15.04 ± 3.31	12.47 ± 2.09
	UW	7.35 ± 1.26	6.75±1.50
	NI	15.50 ± 2.54	13.16 ± 1.68
	UW	7.35 ± 1.26	6.75 ± 1.50
	AP	15.50 ± 2.54	13.16 ± 1.68
	STR	15.04 ± 3.31	12.47± 2.09
	LV	9.13 ± 0.78	9.08 ± 0.82
	STR	15.04 ± 3.31	12.47± 2.09
	PD	9.82 ± 0.06	9.79 ± 0.04
	NI	15.50 ± 2.54	13.16 ± 1.68
	LV	9.13 ± 0.78	9.08 ± 0.82
	NI	15.50 ± 2.54	13.16± 1.68
	PD	9.82 ± 0.06	9.79 ± 0.04
	AP	15.50 ± 2.54	13.16 ± 1.68
	LV	9.13 ± 0.78	9.08 ± 0.82
	AP	15.50 ± 2.54	13.16 ± 1.68
	PD	9.82 ± 0.06	9.79 ± 0.04

Note: HPG_J = high jump performance group, LPG_J = low jump performance group, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

Table 4.8 Summary of Statistically Significant Post Hoc Interactions for Phase Impulse for the Phase by Jump Performance Interaction for Male Athletes

	Comparison	HPG_J	LPG_J
Relative Impulse ($Ns \cdot kg^{-1}$)	UW	1.45 ± 0.20	1.25 ± 0.18
	NI	2.92 ± 0.16	2.55 ± 0.17
	UW	1.45 ± 0.20	1.25 ± 0.18
	LV	0.14 ± 0.03	0.17 ± 0.02
	UW	1.45 ± 0.20	1.25 ± 0.18
	PD	0.13 ± 0.03	0.16 ± 0.02
	STR	1.41 ± 0.19	1.22 ± 0.18
	NI	2.92 ± 0.16	2.55 ± 0.17
	STR	1.41 ± 0.19	1.22 ± 0.18
	AP	3.07 ± 0.16	2.73 ± 0.16
	STR	1.41 ± 0.19	1.22 ± 0.18
	LV	0.14 ± 0.03	0.17 ± 0.02
	STR	1.41 ± 0.19	1.22 ± 0.18
	PD	0.13 ± 0.03	0.16 ± 0.02
	NI	2.92 ± 0.16	2.55 ± 0.17
	AP	3.07 ± 0.16	2.73 ± 0.16
	NI	2.92 ± 0.16	2.55 ± 0.17
	LV	0.14 ± 0.03	0.17 ± 0.02
	NI	2.92 ± 0.16	2.55 ± 0.17
	PD	0.13 ± 0.03	0.16 ± 0.02
	AP	3.07 ± 0.16	2.73 ± 0.16
	LV	0.14 ± 0.03	0.17 ± 0.02
	AP	3.07 ± 0.16	2.73 ± 0.16
	PD	0.13 ± 0.03	0.16 ± 0.02
	LV	0.14 ± 0.03	0.17 ± 0.02
	PD	0.13 ± 0.03	0.16 ± 0.02

Note: HPG_J = high jump performance group, LPG_J = low jump performance group, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

For female athletes a summary of the phase by jump performance sub-group simple *post hoc* interaction comparisons found to be statistically significant are displayed in tables 4.9, 4.10 and 4.11. When examining plots of the cell means, similar to the male athletes, common patterns were observed in the interactions. For relative magnitude similar positive trends were observed for comparisons of the unweighing phase to the leaving and propulsion-deceleration phases with the HPG_J exhibiting the greatest relative magnitudes in both phases. Negative trends were observed for comparisons of the stretching to propulsion-deceleration phase, the net impulse phase to the leaving, and propulsion-deceleration phases, and the acceleration-propulsion phase to the leaving, and propulsion-deceleration phases. In all comparisons the HPG_J exhibited greater relative magnitude in the stretching, net impulse, and acceleration-propulsion phases. When transitioning to the leaving and propulsion-deceleration phases means for both groups became relatively similar, and consequently the HPG_J exhibited a decrease to a greater extent.

For relative impulse, common trends were also observed in the cell means of the female athletes. Positive trends were observed when comparing the unweighted phase to the net impulse and acceleration-propulsion phases, as well as comparisons of the stretching phase to the net impulse and acceleration-propulsion phases. In all comparisons, relative impulse values were similar for the unweighing and stretching phases between groups, with cell means increasing when transitioning to the net impulse and acceleration-propulsion phases, where the HPG_J displayed the greatest cell means. Similar negative trends were observed in comparisons of the unweighted phase to the leaving, propulsion-deceleration phases, the stretching phase to the leaving and propulsion-deceleration phases, the net impulse phase to the leaving and propulsion-deceleration phases, and the acceleration-propulsion phase to the leaving and propulsion-deceleration phases. In all comparisons cell means decreased toward more similar values, with the HPG_J exhibiting the greatest rate of decrease.

Table 4.9 Summary of Statistically Significant Post Hoc Interactions for Phase Magnitude for the Phase by Jump Performance Interaction for Female Athletes

	Comparison	HPG_J	LPG_J
Relative Magnitude ($N \cdot kg^{-1}$)	UW	7.75 ± 1.07	6.15 ± 1.36
	LV	8.86 ± 0.80	8.33 ± 1.08
	UW	7.75 ± 1.07	6.15 ± 1.36
	PD	9.78 ± 0.05	9.78 ± 0.07
	STR	12.57 ± 2.39	11.03 ± 2.09
	PD	9.78 ± 0.05	9.78 ± 0.07
	NI	13.28 ± 2.09	11.58 ± 2.14
	LV	8.86 ± 0.80	8.33 ± 1.08
	NI	13.28 ± 2.09	11.58 ± 2.14
	PD	9.78 ± 0.05	9.78 ± 0.07
	AP	13.28 ± 2.09	11.58 ± 2.14
	LV	8.86 ± 0.80	8.33 ± 1.08
	AP	13.28 ± 2.09	11.58 ± 2.14
	PD	9.78 ± 0.05	9.78 ± 0.07

Note: HPG_J = high jump performance group, LPG_J = low jump performance group, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

Table 4.10 Summary of Statistically Significant Post Hoc Interactions for Phase Impulse for the Phase by Jump Performance Interaction for Female Athletes

	Comparison	HPG_J	LPG_J
Relative Impulse ($Ns \cdot kg^{-1}$)	UW	1.37 ± 0.18	1.13 ± 0.21
	NI	2.57 ± 0.24	2.15 ± 0.18
	UW	1.37 ± 0.18	1.13 ± 0.21
	AP	2.72 ± 0.23	2.33 ± 0.16
	UW	1.37 ± 0.18	1.13 ± 0.21
	LV	0.14 ± 0.02	0.17 ± 0.04
	UW	1.37 ± 0.18	1.13 ± 0.21
	PD	0.13 ± 0.02	0.16 ± 0.04
	STR	1.33 ± 0.17	1.09 ± 0.19
	NI	2.57 ± 0.24	2.15 ± 0.18
	STR	1.33 ± 0.17	1.09 ± 0.19
	AP	2.72 ± 0.23	2.33 ± 0.16
	STR	1.33 ± 0.17	1.09 ± 0.19
	LV	0.14 ± 0.02	0.17 ± 0.04
	STR	1.33 ± 0.17	1.09 ± 0.19
	PD	0.13 ± 0.02	0.16 ± 0.04
	NI	2.57 ± 0.24	2.15 ± 0.18
	AP	2.72 ± 0.23	2.33 ± 0.16
	NI	2.57 ± 0.24	2.15 ± 0.18
	LV	0.14 ± 0.02	0.17 ± 0.04
	NI	2.57 ± 0.24	2.15 ± 0.18
	PD	0.13 ± 0.02	0.16 ± 0.04
	AP	2.72 ± 0.23	2.33 ± 0.16
	LV	0.14 ± 0.02	0.17 ± 0.04
	AP	2.72 ± 0.23	2.33 ± 0.16
	PD	0.13 ± 0.02	0.16 ± 0.04

Note: HPG_J = high jump performance group, LPG_J = low jump performance group, UW = unweighted phase, STR = stretching phase, NI = net impulse, AP = acceleration-propulsion phase, LV = leaving phase, PD = propulsion-deceleration phase

For shape factor, the both jump performance groups exhibited relatively similar shape factor values for the unweighted phase with the HPG_J exhibiting greater cell means in the stretching phase as compared to the LPG_J. Plots of cell means for comparisons of the stretching, leaving and propulsion-deceleration phases both exhibited disordinal patterns (figure 4.3). This interaction indicates that more proficient jumpers (i.e. HPG_J) exhibit greater shape factor values in the stretching phases as compared to the leaving and propulsion-deceleration phases; whereas less-proficient jumpers exhibit the opposite trend. Although, not statistically significant a similar pattern for these phase variables was observed in the males jumpers as well. To further investigate this relationship, calculations of a shape factor ratio were performed for both the stretching and leaving phase ($STR:LV_{sf}$) as well as the stretching and propulsion-deceleration phases ($STR:PD_{sf}$). For $STR:LV_{sf}$ mean ratios were 0.95 ± 0.14, and 0.98 ± 0.15 for males and females respectively. For the $STR:PD_{sf}$, mean values were 0.99 ± 0.14, and 1.04 ± 0.15 for males and females, respectively. A Pearson's zero-order product-moment correlation coefficient found strong statistically significant correlations between both $STR:LV_{sf}$ ($r = 0.604$, $p < 0.001$, n = 120) and $STR:PD_{sf}$ ($r = 0.503$, $p < 0.001$, n = 120) and jump height.

Table 4.11 Summary of Statistically Significant Post Hoc Interactions for Shape Factor for the Phase by Jump Performance Interaction for Female Athletes

	Comparison	HPG_J	LPG_J
Shape Factor (%)	UW	54.4 ± 4.2	54.0 ± 5.2
	STR	61.6 ± 6.0	55.8 ± 8.2
	STR	61.6 ± 6.0	55.8 ± 8.2
	LV	58.8 ± 2.6	61.1 ± 3.6
	STR	61.6 ± 6.0	55.8 ± 8.2
	PD	56.1 ± 2.9	56.7 ± 3.0

Note: HPG_J = high jump performance group, LPG_J = low jump performance group, UW = unweighted phase, STR = stretching phase, LV = leaving phase, PD = propulsion-deceleration phase

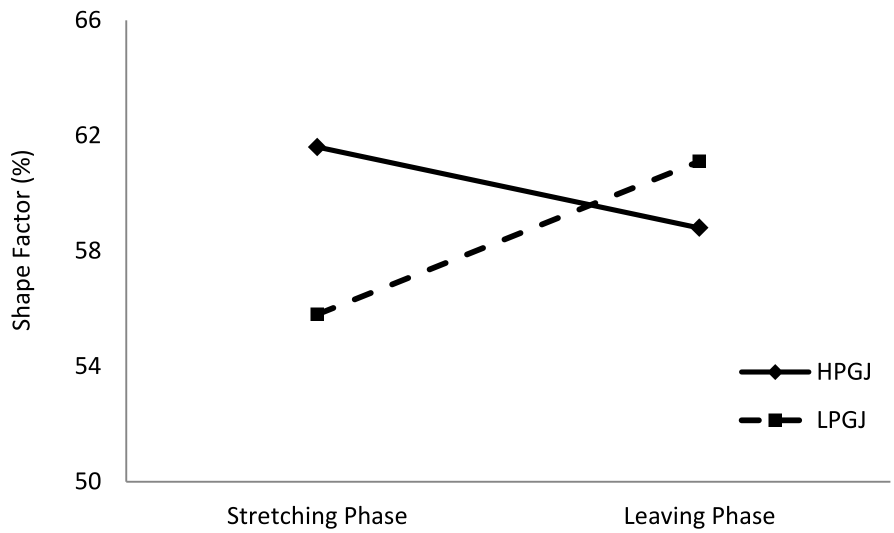

Figure 4.3 Plotted interaction between stretching and leaving phase shape factors observed in females athletes. Note: HPGJ = high jump performance group, LPGJ = low jump performance group

Comparisons of averaged curves for strength performance groups found the averaged normalized curves to be similar between strength performance groups (Figure 4.4). Although differences can be seen in the overall profile of the curves between strength performance groups, there existed no areas of non-overlap in 95% confidence limits for any phase, indicating that any difference in observed in the profile of the phase were with normal variation of the sample.

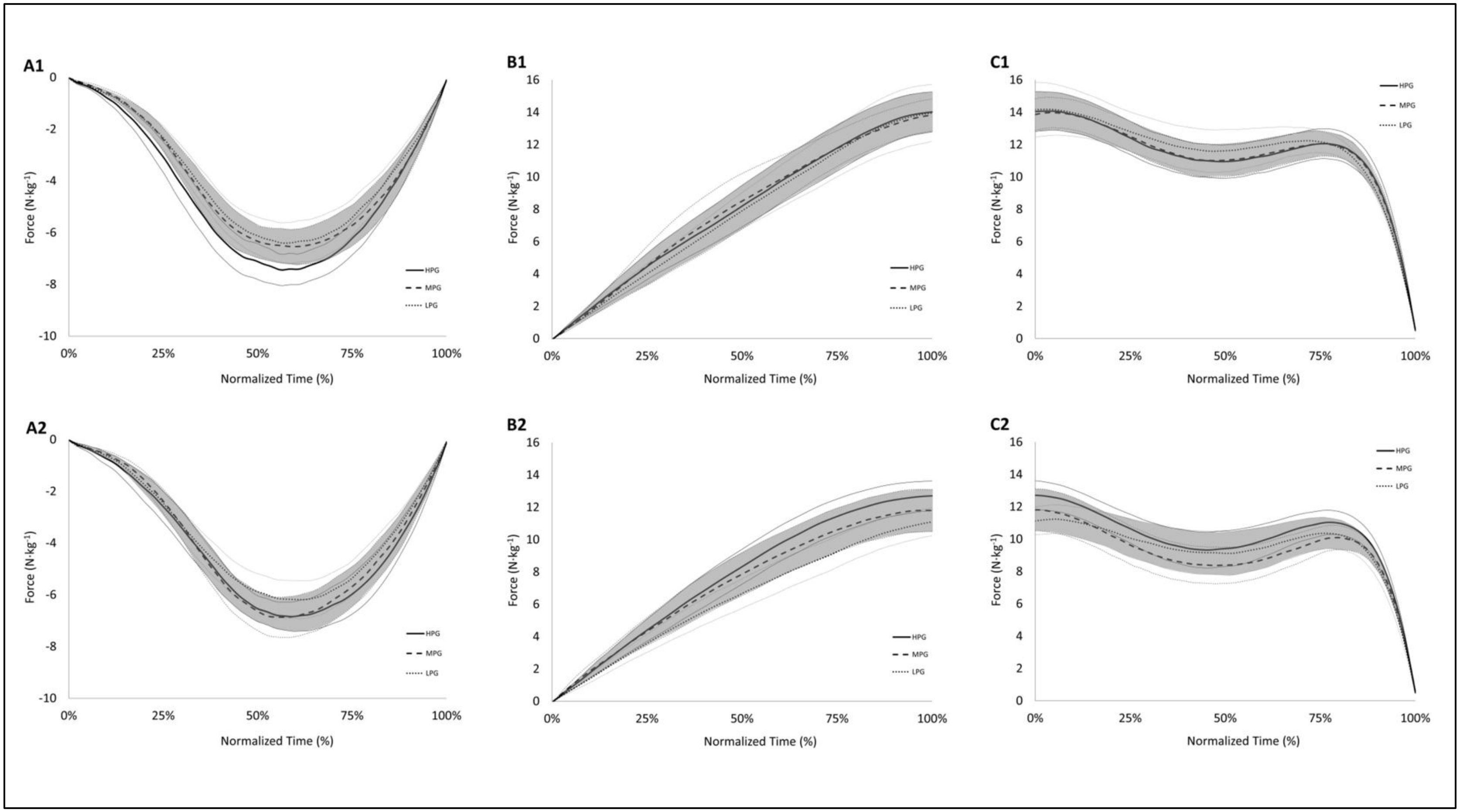

Figure 4.4 Average unweighted (A), stretching (B) and acceleration-propulsion (C) phases for males (A1-C1) and female (A2-C2) athletes. Note: HPG = high-strength performance group, MPG = mid-strength performance group, and LPG = low-strength performance group, Bolded lined represent the group mean and thin lines represent upper and lower 95% confidence limits. Shaded areas represent overlap of two or more of the 95% confidence limits calculated for the averaged curves of each group

Discussion

The purpose of the present study was to investigate the influence of maximal isometric strength on phase characteristics of the CMJ F-t curve. At the initiation of this investigation it was generally hypothesized that an athlete's level of strength (criterion measure IPFa) would influence the profile of the CMJ F-t curve including alterations in size, shape, and temporal structure of the curve. This assumption was based on the findings of previous research noting alterations in F-t curve characteristics (both peak variables as well as the overall shape of the curve itself) following training-induced increases in muscular strength [10-12], as well as differences observed in F-t curve characteristics between strong and weak individuals [13]. Furthermore, these features of the curve could be quantified through assessing the characteristics (size, duration, area, and shape) of the individual phases of the CMJ F-t curve (figure 4.1). The results of the study found only unweighted phase duration to differ statistically between athletes based on maximal isometric strength levels. Specifically, athletes with the greatest IPFa values exhibited a shorter (duration) unweighted phase as compared to their counterparts with lower IPFa values. Furthermore, this result was only present in the analysis of male athletes as unweighted phase durations were relatively similar in the female athletes, irrespective of strength level. Although the exact reasoning for shorter duration unweighted phase observed in males is unknown, some insight may be provided through the results of previous research investigating the unweighted phase and eccentric portion of the CMJ.

The unweighted phase represents a distinct portion of the movement that is unique to the CMJ distinguishing it from other modes of vertical jump. Additionally, this phase represents a portion of the eccentric phase of the movement where the jumper lowers their center of mass and subsequently the vertical ground reaction force falls below system weight. Moreover, the unweighted phase immediately precedes the stretching phase (figure 4.2 points B to C) of the CMJ where the knee extensors and plantar flexors undergo a lengthening "stretch" as concentric muscle action initiates while the momentum of the jumpers center of mass continues downward [27]. The unweighted and stretching phases (collectively the eccentric portion of the CMJ) has been well-studied in the literature particularly the behavior of the neuromuscular system during this sequence as it relates to improved jump performance (i.e. increased jump height). Proposed underlying mechanisms regarding the performance enhancing effect of this portion of the movement [4, 5], include improved force production capacity of the contractile machinery either from the pre-stretch potentiation phenomena [15, 46], increased active state development [4], or simply by placing the muscle in a more-favorable region of its length-tension relationship [19, 20]. Additionally, utilization of stored elastic energy from the stretch of the series elastic components of the muscle have been implicated in explaining the performance augmenting effect of the eccentric phase on force production as well as jump height during the CMJ [8].

Recently, Cormie, McGuigan, Newton [12] conducted an investigation of the effects of explosiveness-focused and strength-focused training on stretch-shortening cycle function, specifically the eccentric phase of the CMJ. The results of the study found that both training for explosiveness and maximal strength resulted in several alterations to the eccentric phase of the CMJ. Namely, increased peak and average power, increased peak and average force, increased velocity, and increased stiffness all during the eccentric phase all contributing to improved performance in the propulsive (concentric) phase of the jump. The results of the present study concerning unweighted duration may be reflective of a similar neuromuscular strategy as that noted by Cormie, McGuigan, Newton [12]. Stronger athletes produced shorter duration of unweighted phases despite similar relative magnitude and impulse as compared to their less-strong counterparts, indicating a similar amount of work performed within a shorter amount of time. Performing a similar amount of work over a shorter duration may result in increased negative velocity and acceleration during the phase. Greater accelerations throughout the unweighted phase may be an attempt to induce a greater stretch on the musculotendionus unit in the subsequent stretching phase to augment concentric performance through one or more of aforementioned mechanisms. Additionally, increased acceleration throughout the unweighted phase may be an attempt to achieve greater muscle activation in order to counter the increased downward momentum of the jumper. However, it is important to note that decreased unweighted phase duration and any other proposed subsequent effects did not reflect in outcome of the movement (i.e. jump height) as the athletes in the HPG_S did not have statistically greater jump heights as compared to the MPG_S and LPG_S.

A secondary finding of this study confirms the findings of our previous investigation [48] indicating that jumpers of different abilities (i.e. jump height) display specific CMJ F-t curve phase characteristics. Namely, more proficient jumpers (both males and female) were associated with greater relative magnitude in the stretching, net impulse and acceleration propulsion phases as well as greater relative impulse in the unweighted, stretching, net impulse and acceleration-propulsion phases. What is a novel finding of this study is that these characteristics seem to belong to proficient jumpers irrespective of isometric maximal strength (IPFa). In other words, similar phase characteristics were observed in both proficient jumpers that are strong and proficient jumpers that are significantly less-strong. This result was true for the analysis of both males and females athletes. Considering the existence of several studies documenting relationship between measures of muscular strength characteristics other than maximal isometric strength, such as dynamic strength [7, 21, 44, 50, 59], and isometric and dynamic rate of force development [21, 26, 28, 51] and CMJ performance, it is possible that one or more of these other strength attributes may more strongly influence CMJ F-t curve characteristics.

Concerning the analysis based on jump performance sub-groups, an interesting relationship was observed in the shape factor values of both the stretching and leaving, and stretching and propulsion-deceleration phases of the F-t curve. This result suggests that more proficient jumpers display a similar or greater shape factor values in the stretching phase relative to their leaving phase, whereas less-proficient jumpers commonly produce lower shape factor values in the stretching phase. Although this result was only statistically significant in female athletes males exhibited a similar pattern in these same variables (figure 4.3). Furthermore, calculations of a shape factor ratio and correlations preformed between jump height and this ratio exhibited a strong statistically significant positive relationship. The mechanisms underpinning these occurrences are presently unknown. However, based on what is known about the mechanical and neuromuscular events occurring within the stretching phase [27], it can be hypothesized that force production, specifically eccentric force production may be a primary contributor to the relationship with jump performance. An increased stretching shape factor indicates the impulse of the phase is occupying a greater portion of the theoretically possible impulse (a rectangle around the impulse, bound by the height [magnitude] and width [duration] of the phase) [1, 14]. One potential way of increasing stretching shape factor is by increasing the magnitude of the phase. In the present investigation better jumpers both males and females exhibited greater stretching phase relative magnitudes. Additionally, stretching shape factor may be increased by increasing the rate of rise in force during this phase (i.e. eccentric rate of force development). Greater eccentric rate of force development will result in a steeper stretching curve, and subsequently a greater shape factor. At least two previous studies have demonstrated a relationship between eccentric rate of force development and CMJ performance (JH)[29, 37]. However, the extant research investigating the role of rate of force development in this specific region of the F-t curve and CMJ performance is unclear. In addition to investigating the influence of rate of force development on JH, previous authors have established relationships between the rise in force in the area corresponding to the stretching phase and neuromuscular characteristics such as percentage of type II muscle fiber [6]. Although further research is warranted regarding the underlying mechanisms of increased STR:LV_{SF}, specifically, factors influencing stretching shape factor. It can be concluded that this variable may hold potential as a monitoring variable of assessing an athlete's training state or progress.

In conclusion with the exception of unweighted phase duration, the results of this investigation were unable to support the hypothesis that maximal isometric strength may be reflected in characteristics of an athlete's CMJ F-t curve phases. The single result found for the phase by strength analysis that unweighted phase duration was shorter in strong male athletes may be related to an altered movement strategy in effort to increase jump performance. However, future research perhaps involving other measures of muscular strength (e.g. dynamic strength, rate of force development, and forces within specific time windows), or a more homogenous sample related to training background (e.g. exclusively strength-trained or explosiveness-trained athletes) may provide clearer results regarding the influence of strength on phase characteristics of the CMJ F-t curve. A secondary but important finding of this study was that proficient jumpers exhibit similar CMJ F-t curve phase characteristic regardless of isometric strength level. This result indicates that there are specific factors other than strength that can be training in order to increase jump performance (i.e. jump height). Based on this finding, future research may focus on elucidating the specific mechanisms (e.g. movement strategies, neuromuscular characteristics) underpinning increased relative phase magnitude and impulse so they may be exploited in training.

Practical Application

The results of this investigation indicate that the maximal strength of an athlete as determined by scaled isometric peak force has little influence of the size and shape of individual CMJ F-t curve phases. While only present in the analysis of males, it seems that the duration of the CMJ F-t curve unweighted phase may reflect an athlete's level of maximal strength. Thus, monitoring the duration of this phase in addition to other CMJ performance variables may provide insight into an athlete's level of maximal isometric strength. Additionally, practitioners may consider monitoring the characteristics of the remaining portion of the eccentric phase of the CMJ F-t curve (i.e. the stretching phase) as this phase may reflect an athlete's rate of force development characteristic. Although further research is warranted, regular assessment of these phase characteristics may provide practitioners with additional variables to assess an athlete's performance state and in conjunction with additional training data assist in making training decisions.

References

1. Adamson GT, Whitney RJ. Critical appraisal of jumping as measure of human power. *In Vredenbregt, J. (ed.), Biomechanics II, Baltimore, Md., University Park Press, p.208-211.*; 1971.

2. Balsalobre-Fernandez C, Tejero-Gonzalez CM, del Campo-Vecino J. Hormonal and neuromuscular responses to high-level middle- and long-distance competition. *International Journal of Sports Physiology & Performance.* 2014;9(5):839-844.

3. Balsalobre-Fernandez C, Tejero-Gonzalez CM, del Campo-Vecino J. Relationships between training load, salivary cortisol responses and performance during season training in middle and long distance runners. *PLoS One.* 2014;9(8):e106066.

4. Bobbert MF, Casius LJ. Is the effect of a countermovement on jump height due to active state development. *Medicine & Science in Sports & Exercise.* 2005;37(3):440-446.

5. Bobbert MF, Gerritsen KG, Litjens MC, Van Soest AJ. Why is countermovement jump height greater than squat jump height? *Medicine & Science in Sports & Exercise.* 1996;28:1402-1412.

6. Bosco C, Komi PV. Mechanical characteristics and fiber composition of human leg extensor muscles. *European Journal of Applied Physiology & Occupational Physiology.* 1979;41(4):275-284.

7. Carlock JM, Smith SL, Hartman MJ, et al. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *The Journal of Strength & Conditioning Research..* 2004;18(3):534-539.

8. Cavagna G, Saibene F, Margaria R. Effect of negative work on the amount of positive work performed by an isolated muscle. *Journal of Applied Physiology.* 1965;20(1):157-158.

9. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *Journal of Applied Biomechanics.* 2008;24(2):112.

10. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength & Conditioning Research.* 2009;23(1):177-186.

11. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Medicine & Science in Sports & Exercise.* 2010;42(8):1582-1598.

12. Cormie P, McGuigan MR, Newton RU. Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sports & Exercise.* 2010;42(9):1731-1744.

13. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine & Science in Sports & Exercise.* 2010;42(8):1566-1581.

14. Dowling JJ, Vamos L. Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics.* 1993;9:95-95.

15. Ettema GJ, Huijing PA, de Haan A. The potentiating effect of prestretch on the contractile performance of rat gastrocnemius medialis muscle during subsequent

shortening and isometric contractions. *Jouranl of Expermental Biology*. 1992;165:121-136.

16. Gathercole RJ, Sporer BC, Stellingwerff T. Countermovement Jump Performance with Increased Training Loads in Elite Female Rugby Athletes. *International Journal of Sports Medicine.* 2015.

17. Gathercole RJ, Sporer BC, Stellingwerff T, Sleivert G. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology & Performance.* 2015;10(1):84-92.

18. Gathercole RJ, Stellingwerff T, Sporer BC. Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *The Journal of Strength & Conditioning Research.* 2015;29(1):37-46.

19. Gordon AM, Huxley AF, Julian FJ. Tension development in highly stretched vertebrate muscle fibres. *The Journal of Physiology.* 1966;184(1):143-169.

20. Gordon AM, Huxley AF, Julian FJ. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of Physiology.* 1966;184(1):170-192.

21. Haff GG, Carlock JM, Hartman MJ, et al. Force-Time Curve Characteristics of Dynamic and Isometric Muscle Actions of Elite Women Olympic Weightlifters. *The Journal of Strength & Conditioning Research.* 2005;19(4):741-748.

22. Haff GG, Stone MH, O'Bryant HS, et al. Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions. *The Journal of Strength & Conditioning Research.* 1997;11(4):269-272.

23. Holm S. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics.* 1979:65-70.

24. Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Medicine.* 2000;30(1):1-15.

25. Juneja H, Verma S, Khanna G. Isometric Strength and Its Relationship to Dynamic Performance: A Systematic Review. *Journal of Exercise Science &Physiotherapy.* 2010;6(2):60-69.

26. Kawamori N, Rossi SJ, Justice BD, et al. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J Strength Cond Res.* 2006;20(3):483-491.

27. Kibele A. Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics.* 1998;14:105-117.

28. Kraska JM, Ramsey MW, Haff GG, et al. Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology & Performance.* 2009;4(4):461-473.

29. Laffaye G, Wagner PP, Tombleson TIL. Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables. *The Journal of Strength & Conditioning Research.* 2014;28(4):1096-1105.

30. Lees A, Vanrenterghem J, Clercq DD. Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics.* 2004;37(12):1929-1940.

31. Levine TR, Hullett CR. Eta Squared, Partial Eta Squared, and Misreporting of Effect Size in Communication Research. *Human Communication Research.* 2002;28(4):612-625.

32. Linthorne N. Analysis of standing vertical jumps using a force platform. *American Journal of Physics.* 2001;69:1198.

33. Marques MC, Izquierdo M, Van den Tillaar R, Moir GL, Sanchez-Medina L, Gonzalez-Badillo JJ. The reliability of force-time variables recorded during vertical jump performance and their relationship with jump height in power trained athletes. *International Sport Medicine Journal.* 2014;15(2):146-155.

34. McBride JM, Triplett-McBride T, Davie A, Newton RU. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *The Journal of Strength & Conditioning Research.* 1999;13(1):58-66.

35. McGuigan MR, Winchester JB. The Relationship Between Isometric and Dynamic Strength in College Football Players. *Journal of Sports Science & Medicine.* 2008;7(1):101-105.

36. McGuigan MR, Winchester JB, Erickson T. The importance of isometric maximum strength in college wrestlers. *Journal of Sports Science &Medicine.* 2006;5(CSSI):108-113.

37. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. *The Journal of Strength & Conditioning Research.* 2011;25(2):379-385.

38. McMaster D, Gill N, Cronin J, McGuigan M. A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine.* 2014;44(5):603-623.

39. Mizuguchi S. Net Impulse and Net Impulse Characteristics in Vertical Jumping (Doctoral dissertation). *East Tennessee State University, Johnson City, TN.* 2012.

40. Moir GL, Button C, Glaister M, Stone MH. Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *The Journal of Strength & Conditioning Research.* 2004;18(2):276-280.

41. Moir GL, Garcia A, Dwyer G. Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology & Performance.* 2009;4(3):317.

42. Moir GL, Sanders R, Button C, Glaister M. The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *The Journal of Strength & Conditioning Research.* 2005;19(1):140-145.

43. Moir GL, Shastri P, Connaboy C. Intersession reliability of vertical jump height in women and men. *The Journal of Strength & Conditioning Research.* 2008;22(6):1779-1784.

44. Nuzzo JL, McBride JM, Cormie P, McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *The Journal of Strength & Conditioning Research.* 2008;22(3):699-707.

45. Psycharakis SG, Miller S. Estimation of errors in force platform data. *Res Q Exercise Sport.* 2006;77(4):514-518.

46. Rassier DE. Molecular basis of force development by skeletal muscles during and after stretch. *Molecular Cell Biomechanics.* 2009;6(4):229-241.

47. Richter C, O'Connor NE, Marshall B, Moran K. Analysis of characterizing phases on waveform: an application to vertical jumps. *Journal of Applied Biomechanics.* 2014;30(2):316-321.

48. Sole CJ. Analysis of the Phase Characteristics of the Countermovement Vertical Jump in Athletes (Doctoral dissertation). *East Tennessee State University, Johnson City, TN.* 2015.

49. Sole CJ, Mizuguchi S, Suchomel TJ, Sands WA, Stone MH. Longitudinal monitoring of countermovement jump mechanical variables: A preliminary investigation. *In proceedings of: XXXII Congress of the International Society of Biomechanics in Sports, Johnson City, Tennessee.* 2014.

50. Stone MH, O'Bryant H, McCoy L, Coglianese R, Lehmkuhl M, Schilling B. Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps. *The Journal of Strength & Conditioning Research.* 2003;17(1):140-147.

51. Stone MH, Sands WA, Carlock J, et al. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *The Journal of Strength & Conditioning Research.* 2004;18(4):878-884.

52. Stone MH, Sands WA, Pierce KC, Carlock J, Cardinale M, Newton RU. Relationship of maximum strength to weightlifting performance. *Medicine & Science in Sports & Exercise.* 2005;37(6):1037-1043.

53. Street G, McMillan S, Board W, Rasmussen M, Heneghan JM. Sources of Error in Determining Countermovement Jump Height With the Impulse Method. *Journal of Applied Biomechanics.* 2001;17:43-54.

54. Tabachnick BG, Fidell LS. *Experimental designs using ANOVA*: Thomson/Brooks/Cole; 2007.

55. Taylor KL, Chapman DW, Cronin JB, Newton MJ, Gill ND. Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning.* 2012;20(1):12-23.

56. Thomas C, Jones PA, Rothwell J, Chiang C-Y, Comfort P. An Investigation into the Relationship between Maximum Isometric Strength and Vertical Jump Performance. *The Journal of Strength & Conditioning Research. (Published ahead of Print).* 2015.

57. Ugrinowitsch C, Tricoli V, Rodacki AL, Batista M, Ricard MD. Influence of training background on jumping height. *The Journal of Strength & Conditioning Research.* 2007;21(3):848-852.

58. Winter DA, Sidwall HG, Hobson DA. Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics.* 1974;7(2):157-159.

59. Wisløff U, Castagna C, Helgerud J, Jones R, Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine.* 2004;38(3):285-288.

60. Yu B, Gabriel D, Noble L, An K-N. Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *Journal of Applied Biomechanics.* 1999;15:318-329.

CHAPTER 5

MONITORING COUNTERMOVEMENT JUMP FORCE-TIME CURVE PHASE CHARACTERISTICS: A CASE STUDY

Authors: [1]Christopher J. Sole, [1]Satoshi Mizuguchi, [1]Kimitake Sato, [2]Gavin L. Moir, and [1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Exercise Science, East Stroudsburg University of Pennsylvania, East Stroudsburg, PA, USA

ABSTRACT

Purpose: To examine the behavior of countermovement jump (CMJ) force-time (F-t) curve phase characteristics over the course of a training process in three individual athletes of varying relative strength levels. ***Methods:*** Weekly CMJ monitoring data from three NCAA Division I women's volleyball athletes were included in this study. CMJ performance monitoring data were examined over the course of eleven weeks of out-of-season training. Phase characteristics from both eccentric and concentric phases of the movement were assessed. The behavior of CMJ F-t curve phase characteristics from week to week and between training periods were assessed through estimations of "likely" meaningful change and a non-parametric trend analyses technique (Tau-U). ***Results:*** Each of the three athletes exhibited markedly different behaviors in CMJ F-t curve characteristics over the eleven-week training period. Trend analysis revealed statistically significant ($p \leq 0.05$) negative trends in CMJ F-t curve characteristics across training periods in the athlete with the lowest relative strength, whereas the athletes with the greater relative strength exhibited improved or maintained these characteristics. ***Conclusion:*** The results of this investigation suggest that CMJ F-t curve phase characteristics may be used to longitudinally monitor an athlete's explosive performance state. Additionally, stronger athletes may be better suited to withstand the demands of training and maintain indicators of explosive performance.

Keywords: *Countermovement jump, athlete monitoring, force-time curve*

Introduction

Assessing an athlete's current performance state and progress throughout a training process is an integral component of effectively implementing a training program. The most common method for assessing an athlete's performance state is thorough indirect measures of muscular performance. Data provided by these tests are then interpreted by the coach and sport scientist and used to assess training progress and/or the outcomes.

The countermovement vertical jump (CMJ) test has become one of the most popular assessments currently used in athlete performance monitoring (Taylor, Chapman, Cronin, Newton, & Gill, 2012) as it has been found a reliable and relatively non-fatiguing assessment of lower-body explosiveness (Moir, Button, Glaister, & Stone, 2004; Moir, Garcia, & Dwyer, 2009; Moir, Sanders, Button, & Glaister, 2005). Additionally, the practical and non-invasive nature of this test allows for it to be frequently implemented throughout a training process, resulting in minimal disruption in scheduled training. Consequently, practitioners may regularly test an athlete's CMJ performance in order to evaluate the athlete's performance state (fatigue, recovery, adaptation) in response to training and competition.

It has been demonstrated that individuals respond to imposed stressors such as training stimuli in a characteristic yet idiosyncratic manner (Lacey, Bateman, & Vanlehn, 1953). In the context of athlete performance monitoring this adds a level of complexity to the interpretation of testing data. When dealing with multiple individuals such as in team sports, inter-individual variation in training responses, presents a problem when attempting to generalize the results of testing to the group. However, if practitioners can identify sources of variation in athlete responses the interpretation of monitoring data can be adjusted accordingly. One potentially substantial contributing factor to variation in training response and testing results is an athlete's level of muscular strength (Stone, Moir, Glaister, & Sanders, 2002). There exist a multitude of evidence documenting the distinctions between stronger athletes and their weaker counterparts that could profoundly impact the training process. For example, stronger individuals have been shown to possess greater level of fatigue resistance (Hamada, Sale, MacDougall, & Tarnopolsky, 2003; Stone, Sands, Pierce, Ramsey, & Haff, 2008). Additionally, stronger individuals have been shown to respond more favorably, and to a greater degree to potentiation protocols and complex paring of exercises (Jo, Judelson, Brown, Coburn, & Dabbs, 2010; Seitz, de Villarreal, & Haff, 2014). Finally, there exists evidence that initial strength levels may dictate how an individual adapts to explosive-type training (Cormie, McGuigan, & Newton, 2010b; Minetti, 2002; Zamparo, Minetti, & di Prampero, 2002). Together these factors could substantially influence an athlete's short- and long-term response to training stimuli. Thus, athlete strength levels should be carefully considered when implementing and interpreting performance monitoring data.

In our previous two investigations (Sole, 2015) we explored the use of analyzing the characteristics of individual phases of the CMJ force-time (F-t) curve in effort to gain a mechanistic understanding of CMJ performance. The results of these studies revealed a phase-by-phase analysis of the CMJs F-t curve was able to identify characteristics shared among proficient jumpers. Specifically, better jumpers were associated with greater relative magnitude and impulse throughout the phases contained within the positive impulse of the CMJ F-t curve. Additionally, the relative shape of the CMJ F-t curve stretching phase was found to relate to jump performance (i.e. jump height [JH]). Considering CMJ is a general measure of lower-body explosiveness and the criterion performance variable for the CMJ is often JH, some phase characteristics of proficient jumpers consequently can be considered characteristics of explosive performance. Therefore, a phase-by-phase mechanistic analysis of the CMJ F-t curve may provide practitioners with a detailed picture of an athlete's explosive state. Consequently, longitudinally tracking CMJ F-t curve phase characteristics may be an effective way of monitoring changes in an athlete's explosiveness throughout a training process. Considering these characteristics are mechanistic in nature, they may prove more effective in assessing changes in an athlete's explosive performance state as compared to peak or outcome variables. However, to the knowledge of the authors, there has yet to be any investigation into the behavior of these F-t curve phase characteristics over time in the context of a training process. Additionally, considering the potentially great influence of an athlete's strength level on elements of training response, recovery, and adaptation, it is likely the behavior of these characteristics may vary between athletes of different muscular strength levels. Therefore the purpose of this study was to examine the behavior of CMJ F-t curve phase characteristics over the course of a training process in three individual athletes of varying strength levels.

Methods

All data included in this investigation were collected as part of an ongoing athlete performance monitoring initiative. The methodology and scope of this study were reviewed and approved by the East Tennessee State University Institutional Review Board. All athletes read and signed informed consent documents prior to the inclusion of their data in this investigation.

Study design

The purpose of the present study was to examine the behavior of CMJ F-t time curve characteristics over the course of a training process. In order to fulfil this purpose, measures of reliability and variability of the CMJ F-t curve characteristic were first assessed. Data included in the reliability analysis were collected over the course of six consecutive weeks of training and competition in twelve National Collegiate Athletic Association (NCAA) Division I women's volleyball athletes (age = 20.22 ± 1.0 y, body mass = 69.9 ± 6.9 kg, height = 175.0 ± 7.0 cm). Measures of within athlete variation and retest correlation were calculated for the mean of two maximal CMJs recorded during weekly monitoring. Once measures of intersession reliability and variability were quantified, the behavior of these variables over the course of a training process was assessed through a descriptive case-study of three individual athletes. The examination period consisted of eleven weeks of out-of-season training that was divided into two distinct training periods (period A and B). Period A consisted of a preparatory period where the primary source of training stimuli was high-volume strength-focused resistance training. Period B consisted of a late-preparatory period where the focus of training shifted to technical and tactical sport practice including two informal competitions occurring in week eleven. The descriptive case study followed three individual athletes over this eleven-week period including weekly testing of CMJ and estimates of training load. These three athletes were selected based on the following criteria: 1) all three athletes had the same level of team experience (three years), 2) all three athletes completed the same periodized training plan during the eleven-week observation period, and 3) the three athletes represented the members of the team with the greatest, median, and lowest levels of relative muscular strength as determined by a pre-training period testing session (table 5.1). In addition, all three athletes had consistently participated in the same periodized resistance training program for at least the previous year and a half.

Table 5.1 Athlete Descriptive Data and Criterion Relative Strength Measures

Athlete	Team Experience (y)	Body Mass (kg)	Age (y)	Height (cm)	IPFa ($N \cdot kg^{.67}$)	Back Squat (kg/BdM)
A "High-Strength"	3	70.5	20.5	172.0	315.72	1.8
B "Mid-Strength"	3	71.0	20.4	183.0	209.96	1.6
C "Low-Strength "	3	83.1	21.2	183.0	167.65	1.3

Note: IPFa = allometrically scaled isometric peak force obtained during isometric mid-thigh pull testing(Kraska et al., 2009); Back Squat (kg/BdM) = the athletes maximum back squat relative to their body mass, estimated from a 5- repetition maximum performed in training the week prior to the examination period

Countermovement jump testing and analysis

All CMJ testing sessions were held on the first training day of the training microcycle (week) immediately prior to an organized team training session. To minimize variability associated with CMJ testing, the time of day of all testing sessions was standardized throughout the examination period (Taylor, Cronin, Gill, Chapman, & Sheppard, 2010). Upon arrival to the sport science laboratory, athletes performed a standardized general warm-up followed by two sub-maximal (50% and 75% of perceived maximum effort) CMJs as a specific warm up. Two maximal CMJ were then measured separated by approximately 30 seconds. To obviate the use of an arm swing, athletes performed all jumps while holding a near-weightless (< 1 kg) plastic bar (Carlock et al., 2004; Kraska et al., 2009; McBride, Triplett-McBride, Davie, & Newton, 1999; Stone et al., 2003). All jumps were performed on a custom-built uniaxial portable force platform (70.0 cm x 70.0 cm) (Major, Sands, McNeal, Paine, & Kipp, 1998). Voltage data from the force platform were collected using an analog-to-analog BNC interface box (BNC-2110), and 16-bit analog-to-digital board (NI PCI-6036E) and custom program (LabVIEW ver. 12.0, National

Instruments, Austin, TX, USA). Based on recommendations for minimizing measurement error, data from all testing sessions were sampled at a frequency of 1000 Hz (Hori et al., 2009; McMaster, Gill, Cronin, & McGuigan, 2014; Street, McMillan, Board, Rasmussen, & Heneghan, 2001) and the force platform was regularly calibrated throughout the examination period (Psycharakis & Miller, 2006).

Following data collection regression equations from laboratory calibration were used to convert force platform voltage data into vertical ground reaction force and F-t curves were constructed. All ground reaction force data were processed using a fourth-order low-pass Butterworth digital filter (Winter, Sidwall, & Hobson, 1974) with an optimum cutoff frequency of 40 Hz (Yu, Gabriel, Noble, & An, 1999) in order to reduce random noise in the signal. In order to represent a more typical score (Henry, 1967) the average of the two CMJ trials were used for all analyses. From the F-t curves the following phases of CMJ F-t curve were determined based on previous research (figure 5.1): unweighted phase, stretching phase, and acceleration-propulsion phase (Kibele, 1998; Linthorne, 2001; Mizuguchi, 2012; Sole, 2015; Ugrinowitsch, Tricoli, Rodacki, Batista, & Ricard, 2007). This investigation was limited to the three of the CMJ F-t curve phases; two from the eccentric portion of the movement (the unweighted and stretching phases) and one from the concentric or propulsive portion of the movement (the acceleration-propulsion phase). These specific phases were selected based on the following rationale: previous investigations have reported that training-related improvements in explosiveness performance and stretch-shortening cycle function may be detected in eccentric phase variables (Cormie, McGuigan, & Newton, 2010a), additionally, characteristics of the unweighted phase specifically duration and shape may be related to an athlete’s strength level (Sole, 2015), and overall jump performance (Garhammer & Gregor, 1992) finally, the eccentric phase of the CMJ is speculated to be sensitive to neuromuscular fatigue (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015). The acceleration-propulsion phase was included considering it is a phase whose characteristic are related to outcome of the movement (i.e. JH) (Sole, 2015); and any alterations in the preceding phases (i.e. eccentric phases) are likely to be reflected in this phase (Cormie et al., 2010a). The following phase characteristics were then calculated for each phase: 1) phase duration, calculated as the length of the phase in milliseconds, 2) phase magnitude, calculated as the height of the phase in newtons (N), 3) phase impulse, expressed in newton-seconds (Ns), and 4) phase shape factor, calculated as a ratio (expresses as a percentage) of the phase impulse relative to a rectangular shape formed around the impulse (Dowling & Vamos, 1993; Mizuguchi, 2012; Sole, 2015). Additionally, the slope of the rise in force during the stretching phase was calculated to represent eccentric rate of force development (RFD) (figure 5.1). Eccentric rate of force development was selected due to its ability to characterize the rate of rise in the stretching phase, which has been suggested as a potential factor leading to increased stretching phase shape factor; a characteristics associated with explosive performance (Sole, 2015). To account for any fluctuations in athlete's body mass, both phase magnitude and impulse were scaled to the system weight of the jumper and expressed as newtons per kg ($N \cdot kg^{-1}$) and newton-seconds per kg ($Ns \cdot kg^{-1}$), respectively. In addition to CMJ F-t curve phase characteristics jump height was also included in this analysis considering its common use as a CMJ performance variable. All data processing and analyses were performed using a custom program (LabVIEW ver. 12.0, National Instruments, Austin, TX, USA).

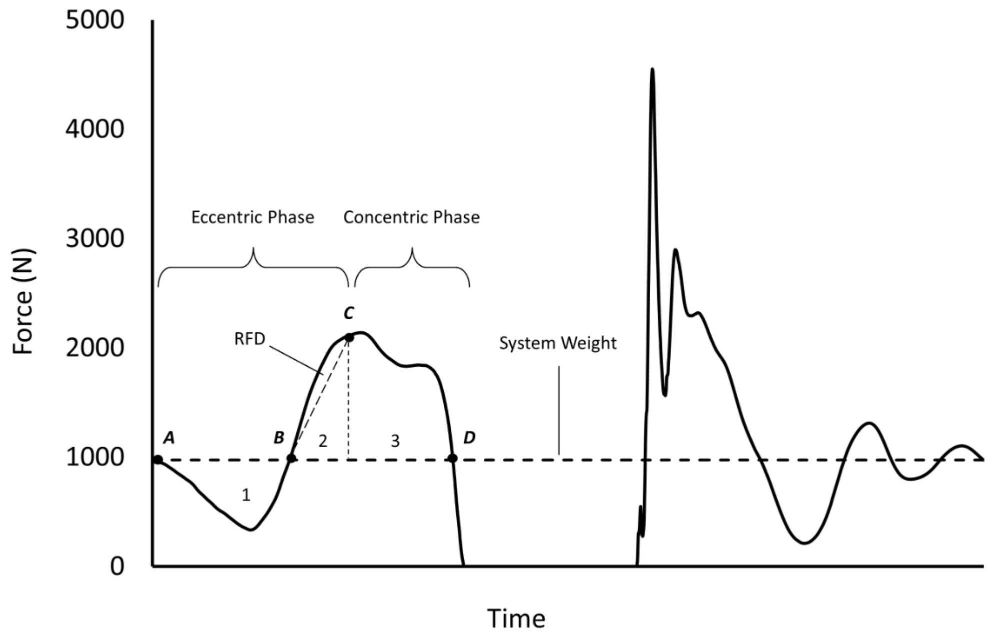

Figure 5.1 Countermovement jump F-t curve. Points A to B: unweighing phase, points B to C: stretching phase, points C to D: acceleration-propulsion phase. Area 1: unweighted impulse, area 2: stretching impulse, and area 3: acceleration-propulsion impulse. *Note: RFD = rate of force development*

Estimates of training load

To indirectly quantify the physiological demands of training, estimates of training load were calculated following each training session. As an estimate of internal training load (Halson, 2014), a session rating of perceived exertion (sRPE) was obtained from each athlete using previously established methods (Foster et al., 2001). Briefly, no sooner that fifteen minutes following the training session athletes were asked to rate their level of perceived exertion on scale ranging from 0-10 (figure 2). The category ratio rating scale and procedures were modified from previously published research (Day, McGuigan, Brice, & Foster, 2004; Foster et al., 2001). Each athlete's sRPE values were then multiplied by the duration of the session to form a sRPE training load (RPETL), expressed in arbitrary units (AU). In addition, the physiological demands of resistance training sessions were estimated through calculations of volume load; a common method of quantifying resistance training dosage (Stone, Stone, & Sands, 2007). Volume load was calculated for all exercises as the product of the mass of the barbell (kg) and the total number of repetitions for a given exercise.

Rating	Descriptor
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	-
7	Very Hard
8	-
9	-
10	Maximal

Figure 5.2 Modified Rating of Perceived Exertion scale with descriptive terms

Statistical analyses

Intrasession reliability and variability of the CMJ F-t curve phase characteristics were assessed using interclass correlation coefficient (ICC), typical error expressed as an absolute value, and typical error expressed as a coefficient of variation of the log-transformed variable (Hopkins, 2000). Additionally, 90% confidence limits were calculated for all the aforementioned measures. To assess the behavior of CMJ F-t curve phase characteristics, weekly changes in the characteristics were compared to the baseline measure obtained in week one. To provide a measure of the practical significance of a weekly change, probabilities of clinically meaningful changes were estimated using previously outlined methods (Hopkins, 2002). Briefly, the weekly change in a variable was compared to a reference value determined to represent a meaningful change. This analysis used the smallest worthwhile change (SWC) (Hopkins, 2000) as the reference value to estimate probabilities. The SWC of a variable was determined according to the suggestions of previous authors as two-times the typical error associated with that variable (Hopkins, 2000; Moir et al., 2009; Smith & Hopkins, 2011). Additionally, qualitative terms were assigned to probability values associated with the weekly changes in CMJ variables as the following: < 1%, almost certainly not; < 5%, very unlikely; < 25%, unlikely; 25-75%, possibly; >75%, likely, > 95%, very likely; and > 99%, almost certain (Hopkins, 2002; Taylor et al., 2010). To investigate changes in CMJ F-t phase characteristics between training phase (phase A and B), a non-parametric trend analysis technique, the Tau-U (Parker, Vannest, Davis, & Sauber, 2011) was utilized for each variables for each athlete, with correction for phase A trend preformed when necessary. Statistical analyses were performed using Statistical Package for Social Sciences (IBM SPSS Statistics for Windows, Version 22.0, IBM Corp., Armonk, NY). Meaningful change probabilities were calculated using a customized Microsoft excel spreadsheet (Microsoft Corp. Redmond WA.) downloaded from *https://www.sportsci.org*. Tau-U analyses were performed using web-based application available at *http://www.singlecaseresearch.org/calculators/tau-u.*

Results

The results of this reliability analysis (table 5.2) found all CMJ F-t curve phase characteristics to have acceptable within subject variation and retest correlation. An exception to this was unweighted phase shape factor. Although this characteristics possessed low within subject variation (CV = 6.5%), retest correlation was poor (ICC = 0.574). Measures of reliability and variability provided typical errors for calculations of SWC. For the unweighted phase, duration relative magnitude and relative impulse exhibited “likely” meaningful (>75% probability) changes (figure 5.3). For the stretching phase RFD was the only characteristics to exhibit a “likely” meaningful change (Figure 5.4). For the acceleration-propulsion phase, both duration and shape factor exhibited “likely” meaningful changes (figure 5.5). Finally, a likely meaningful change was observed in JH (Figure 5.5). Overall these changes occurred in weeks 3, 4, 5, 8, and 10.

Results of the Tau-U analysis are displayed in table 5.3. The Tau statistic has been converted to a percentage representing the amount of non-overlapping data points between training periods (Table 5.3). Therefore, a Tau value of 83.3 such as in the analysis of unweighted duration in athlete A, indicates that 83.3% of the data are non-overlapping when comparing training period A to period B. Examination of the respective time-series plot for this variable reveals the non-overlap is caused by the decrease in unweighted phase duration occurring in training period B. The Tau-U analysis found JH did not exhibit any statistical non-overlap while duration and/or magnitude consistently showed a statistical non-overlap for all of the examined periods. Statistically significant trends were observed in unweighted phase duration and relative magnitude, stretching phase duration and relative magnitude, RFD, and acceleration-propulsion phase shape factor (table 5.3). Specifically, a statistically significant decrease in unweighted phase duration and increase in relative magnitude was observed in athlete A when comparing the two training phases (A vs. B). Although not statistically significant, similar and opposite patterns were observed in athletes B and C, respectively. For the stretching phase, athlete C exhibited a statistically significant increase phase duration and a decrease in relative phase magnitude when comparing training period A to B. Again, although not statistically significant one can see from reviewing the time-series plots (figure 5.4A and B) as well as the Tau statistics (table 5.3) that the opposite trend is present in both athletes A and B. For the acceleration-propulsion phase characteristics, statistically significant differences were observed in athlete C between periods for both acceleration-propulsion relative magnitude and relative impulse. Specifically, both of these characteristics were decreased in period B of the training period as compared to period A. In addition, athlete B exhibited a statistically significant decrease in acceleration-propulsion shape factor in period B as compared to period A. For RFD, athlete C exhibited a statistically significant decrease in this characteristic when shifting from training period A to training period B. In fact, the Tau statistics revealed 100% non-overlap in RFD values between periods, indicating that all RFD values were lower in the second training period (figure 5.4E).

Table 5.2 Results of the Reliability Analysis of CMJ F-t Curve Characteristics

Variable	Unit	Typical Error	90% CL	CV%	90% CL	ICC	90% CL
UW_{dur}	ms	25.9	[22.0, 31.9]	7.0	[6.0, 8.7]	0.809	[0.665, 0.916]
UW_{mag}	$N{\cdot}kg^{-1}$	0.47	[0.41, 0.58]	7.2	[6.2, 9.0]	0.753	[0.583, 0.889]
UW_j	$Ns{\cdot}kg^{-1}$	0.07	[0.06, 0.08]	5.6	[4.8, 6.9]	0.768	[0.606, 0.897]
UW_{sf}	%	3.24	[2.78, 4.00]	6.5	[5.5, 8.0]	0.574	[0.360, 0.788]
STR_{dur}	ms	11.5	[9.9, 14.3]	6.2	[5.3, 7.7]	0.893	[0.801, 0.955]
STR_{mag}	$N{\cdot}kg^{-1}$	0.97	[0.83, 1.20]	7.3	[6.2, 9.1]	0.937	[0.879, 0.974]
STR_j	$Ns{\cdot}kg^{-1}$	0.06	[0.06, 0.08]	5.4	[4.6, 6.7]	0.784	[0.627, 0.904]
STF_{sf}	%	3.17	[0.43, 0.76]	5.8	[4.6, 8.3]	0.753	[0.509, 0.899]
RFD	Ns	582	[500, 719]	12.9	[11.0, 16.2]	0.921	[0.849, 0.967]
AP_{dur}	ms	14.9	[12.8, 18.4]	5.3	[4.5, 6.6]	0.891	[0.798, 0.955]
AP_{mag}	$N{\cdot}kg^{-1}$	0.87	[0.75, 1.08]	5.9	[5.0, 7.3]	0.907	[0.826, 0.962]
AP_j	$Ns{\cdot}kg^{-1}$	0.14	[0.12, 0.17]	0.9	[0.8, 1.1]	0.985	[0.978, 0.994]
AP_{sf}	%	4.5	[3.87, 5.56]	6.4	[5.5, 8.0]	0.880	[0.779, 0.950]
JH	m	0.01	[0.01, 0.01]	2.7	[2.3, 3.3]	0.975	[0.950, 0.990]

Note: UW = unweighted phase, STR = stretching phase, RFD = rate of force development, AP = acceleration-propulsion phase, JH = jump height, $_{dur}$ = duration, $_{mag}$ = magnitude, $_{j}$ = impulse, $_{sf}$ = shape factor, CV = typical error expressed as a coefficient of variation, ICC = intraclass correlation coefficient, 90% CL = 90% confidence limits

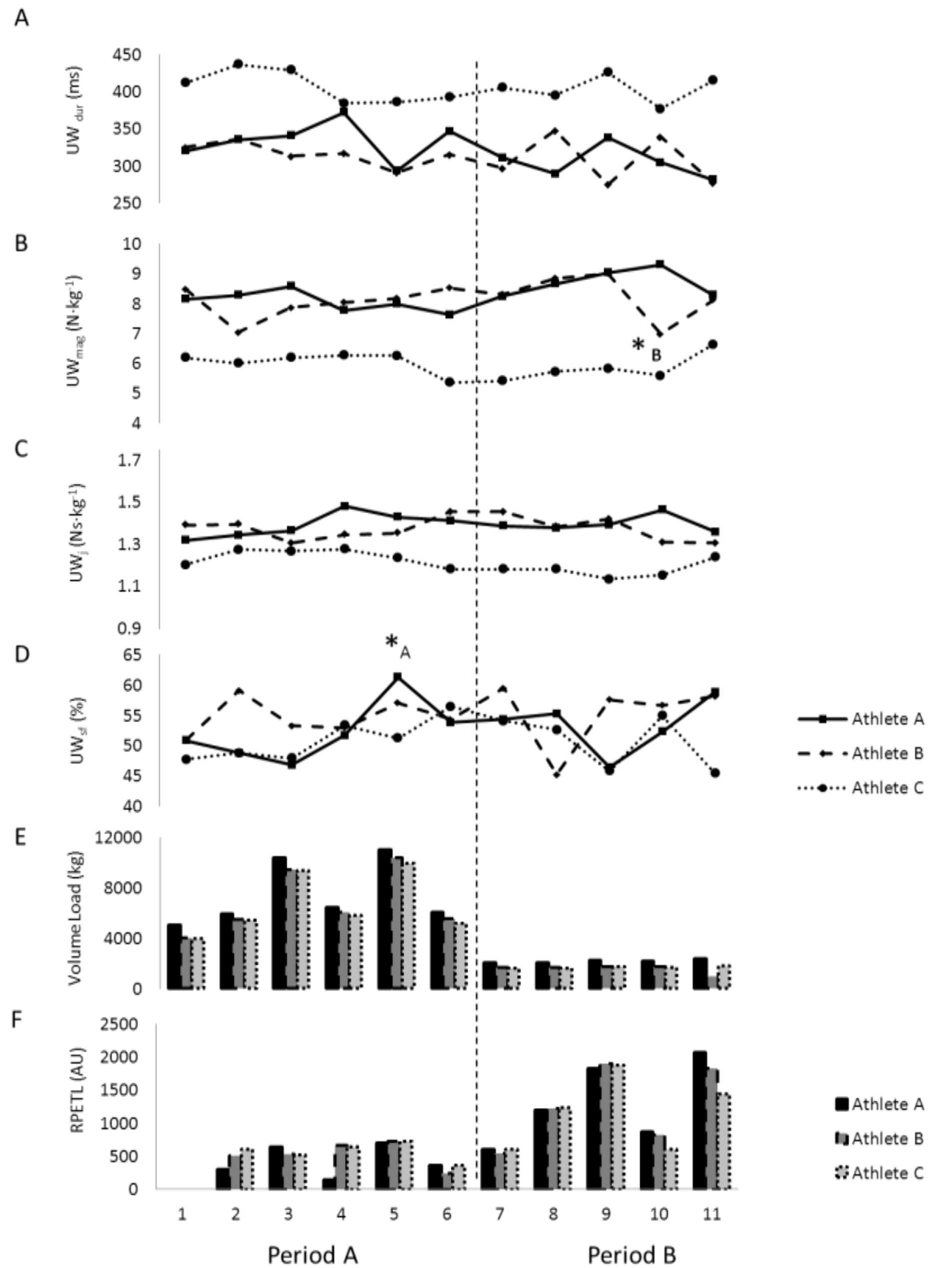

Figure 5.3 Time-series plots of unweighted phase characteristics and training loads. A) Unweighting phase duration, B) unweighted phase relative magnitude, C) unweighted phase relative impulse, D) unweighted phase shape factor, E) resistance training volume load, and F) rating of perceived exertion training load. Note: *A indicates “likely” meaningful change in athlete A, *B indicates “likely” meaningful change in athlete B

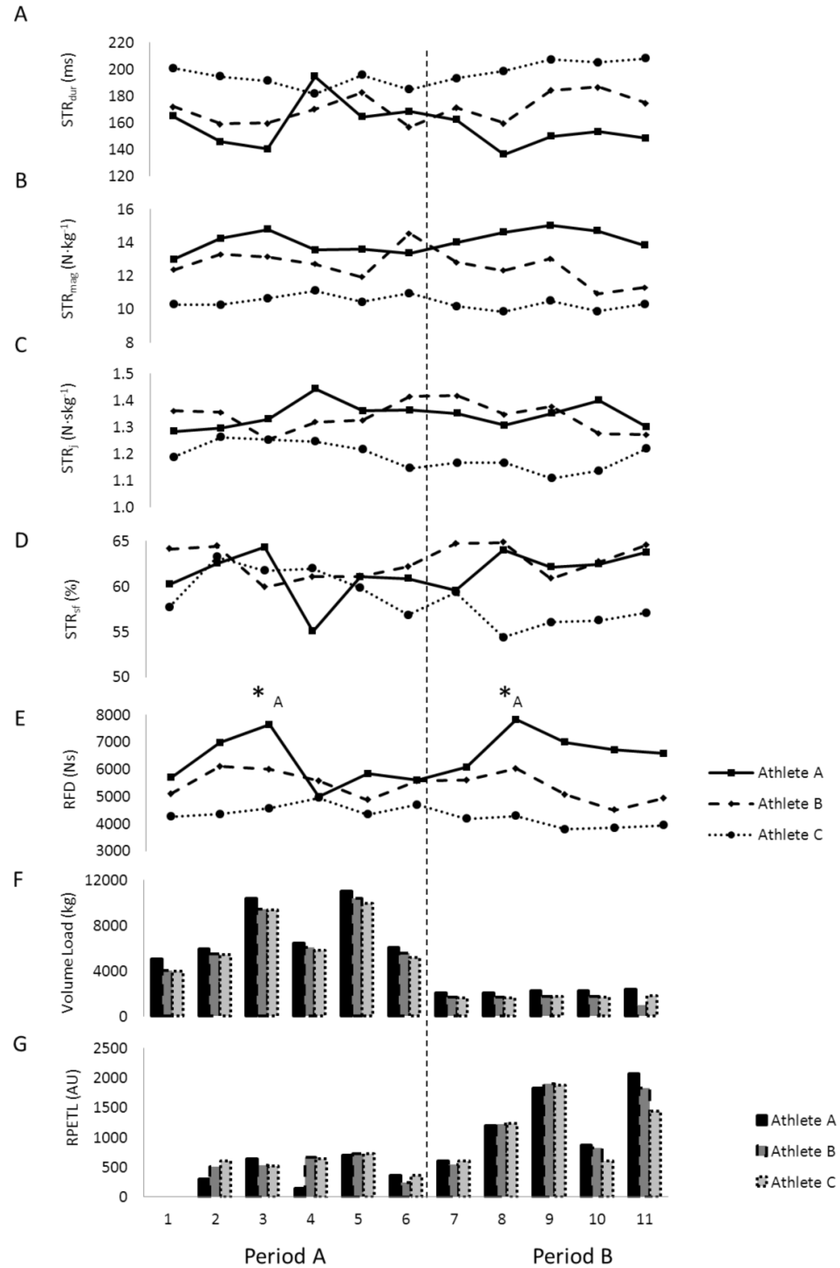

Figure 5.4 Time-series plots of stretching phase variables and training loads. A) Stretching phase duration, B) stretching phase relative magnitude, C) stretching phase relative impulse, D) stretching phase shape factor, E) rate of force development, F) resistance training volume load, and G) rating of perceived training load. Note: *A indicates "likely" meaningful change in athlete A

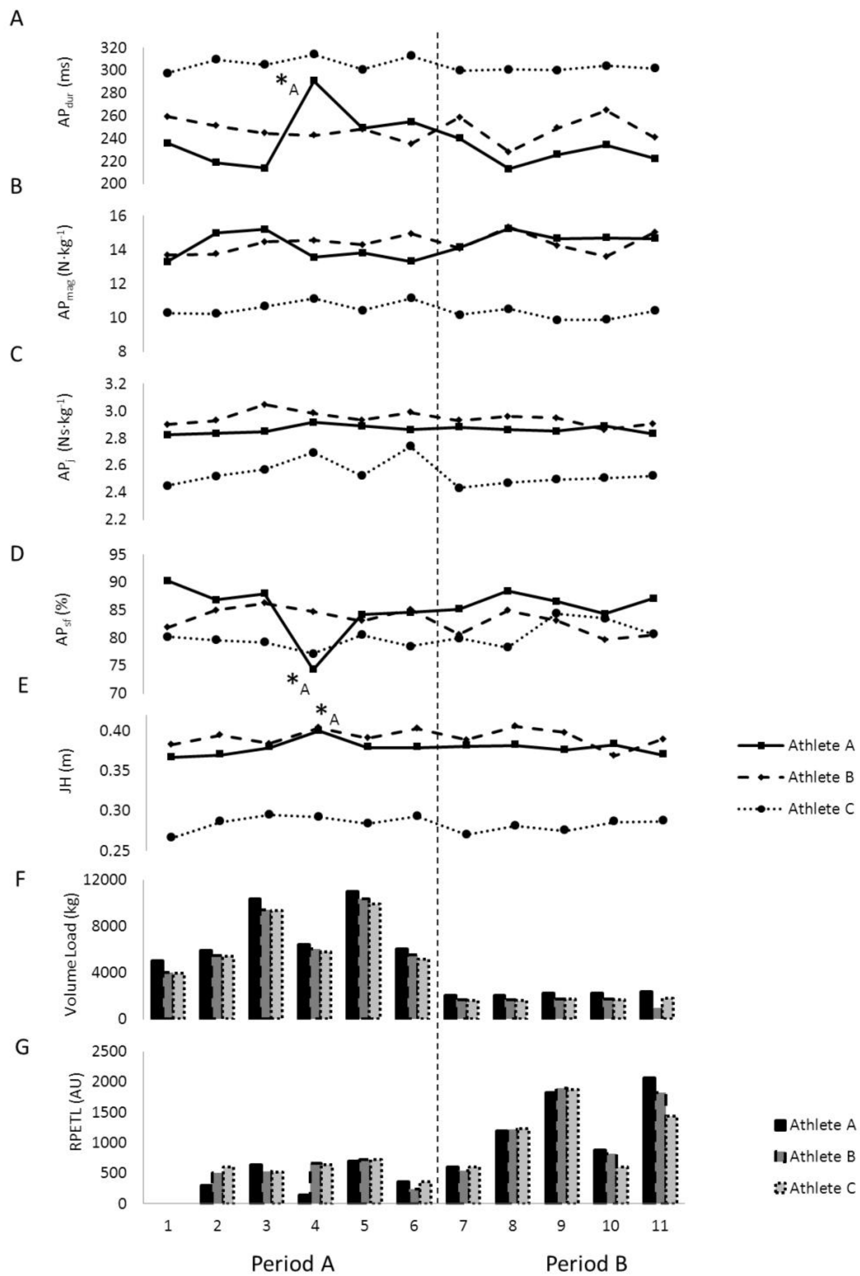

*Figure 5.5*Time-series plots of acceleration-propulsion phase variables and training loads. A) acceleration-propulsion phase duration, B) acceleration-propulsion phase relative magnitude, C) acceleration-propulsion phase relative impulse, D) acceleration-propulsion phase shape factor, E) jump height, F) resistance training volume load, and G) rating of perceived training load. Note: *A indicates "likely" meaningful change in athlete A

Table 5.3 Summary of Tau-U Analysis Between Training Periods

Variable	Athlete	TAU (%)	p	90% CL
UW_{dur}	A*	83.3	0.022	[-1.43, -0.23]
	B	10.0	0.784	[-0.50, 0.70]
	C	10.0	0.784	[-1.43, -0.23]
UW_{mag}	A*	100	0.004	[0.43, 1.63]
	B	3.3	0.927	[-0.57, 0.63]
	C	33.3	0.361	[-0.93, 0.27]
UW_{j}	A	23.3	0.523	[-0.83, 0.37]
	B	6.7	0.855	[-0.67, 0.53]
	C	67.8	0.068	[-1.27, -0.07]
UW_{sf}	A	3.3	0.927	[-0.57, 0.63]
	B	23.3	0.523	[-0.37, 0.83]
	C	43.3	0.235	[-1.03, 0.17]
STR_{dur}	A	56.7	0.121	[-1.17, 0.03]
	B	56.7	0.121	[-0.03, 1.17]
	C*	96.7	0.008	[0.36, 1.57]
STR_{mag}	A	60.0	0.100	[-0.01, 1.201]
	B	53.3	0.144	[-1.13, 0.07]
	C*	90.0	0.014	[-1.50, -0.29]
STR_{j}	A	36.7	0.315	[-0.97, 0.23]
	B	6.7	0.855	[-0.53, 0.67]
	C	43.3	0.235	[-1.03, 0.17]
STR_{sf}	A	26.7	0.465	[-0.33, 0.87]
	B	53.3	0.144	[-0.07, 1.13]
	C	63.3	0.083	[-1.23, -0.03]
RFD	A	63.3	0.083	[0.03, 1.23]
	B	10.0	0.784	[-0.70, 0.50]
	C*	100	0.001	[-1.77, -0.56]
AP_{dur}	A	67.7	0.068	[-1.27 ,-0.07]
	B	43.3	0.235	[-0.17 ,1.03]
	C	56.7	0.121	[-1.17 ,0.04]
AP_{mag}	A	46.7	0.201	[-0.13, 1.07]
	B	30.0	0.411	[-0.90, 0.30]
	C*	96.7	0.008	[-1.57, -0.37]
AP_{j}	A	20.0	0.584	[-0.80, 0.40]
	B	70.0	0.055	[-1.30, -0.10]
	C*	100	0.006	[-1.60, -0.40]
AP_{sf}	A	36.7	0.315	[-0.23, 0.97]
	B*	76.7	0.036	[-1.37, -0.17]
	C	70.0	0.055	[0.10, 1.30]
JH	A	3.3	0.927	[-0.63, 0.57]
	B	30.0	0.411	[-0.90, 0.30]
	C	60.0	0.100	[-1.20, 0.01]

Note: * indicated statistically significant differences between phases $p \leq 0.05$, Note: UW = unweighted phase, STR = stretching phase, RFD = rate of force development, AP = acceleration-propulsion phase, JH = jump height, $_{dur}$ = duration, $_{mag}$ = magnitude, $_{j}$ = impulse, $_{sf}$ = shape factor

Discussion

The purpose of this study was to examine the behavior of CMJ F-t curve phase characteristics over the course of a training process in three individual athletes of varying strength levels. It was hypothesized that an athlete's strength level may affect the behavior of these phase characteristics considering the proposed influence of strength on key elements of training (i.e. fatigue, recovery, and adaptation). In order to evaluate the behavior of these CMJ F-t curve phase characteristics over time, two different analyses were employed: 1) Tau-U trend analysis to compare CMJ F-t curve phase characteristic behavior between training periods, 2) a probability analysis to identify "likely" meaningful weekly changes in these variables. Through these analyses and viewing the data in the context of the training, the potential influence of strength may have been observed in several characteristics.

By analyzing changes in the trend of variables between training periods we can assess how each of the three athletes was individually affected by the transition between periods and shift in training emphasis. Training period A consisted of high-volume strength-focused resistance training as the primary training stimulus. In training period B the volume of resistance training was reduced as the result of a shift towards explosiveness-focused training. Additionally, sport technical and tactical training load increased markedly during this period (period B). A comparison of the three athletes reveals differences in trends for several variables and potential evidence of a strength effect. Jump height for example, remained relatively stable with all three athletes exhibiting no statistically significant trends identified between periods. Interestingly, when reviewing the individual athletes Tau statistics, the percent of non-overlapping data between periods corresponded with the athlete's relative strength ranking (table 5.3). This indicates that the stronger athlete (athlete A) produced the more consistent JHs between periods, whereas the athlete with the lowest relative strength (athlete C) decreased JH following the transition to period B.

Notable trends were also observed in the duration and relative magnitude of the unweighted and stretching phases, RFD, and shape factor for the acceleration-propulsion phase. Regarding the unweighting phase, athlete A exhibited a statistical decrease in these characteristics when comparing training period A to B. Previous research has suggested that an unweighted phase duration may reflect an athlete's strength level; specifically, stronger athletes exhibit shorter unweighted phase durations as compared to less-strong counterparts (Sole, 2015). This finding is partially supported by the fact that in the present study the two stronger athletes exhibited consistently shorter unweighted phases as compared to the weakest athlete (athlete C). When viewed in the context of training the statistical decrease in unweighted phase duration exhibited by athlete A may reflect improvements in strength achieved during period A, or perhaps the maintenance of strength throughout this period.

For the stretching phase, statistical decreases were exhibited by athlete C in phase relative magnitude and RFD, as well as statistical increases in phase duration when comparing training period A to B. Although not statistically significant opposite trends are present in both athletes A and B for these same variables with the exception of RFD. Similarly, acceleration-propulsion phase relative magnitude and impulse exhibited statistically significant decreases in athlete C between the periods. Many of these trends exhibited by athlete C in the second period of training (period B) such as an increase in stretching phase duration and decrease in phase magnitude, and decreased RFD may be an indication of potential effect of fatigue as training loads markedly increased. Previous research has suggested that neuromuscular fatigue can be detected through altered CMJ eccentric phase mechanics (Gathercole, Sporer, et al., 2015; Gathercole, Stellingwerff, & Sporer, 2015). Increased stretching phase duration and decreased relative magnitudes suggest that athlete C was spending a greater amount of time and producing less force during the amortization phase while transitioning from eccentric to concentric action following the countermovement (Kibele, 1998). Interestingly, the stronger athletes do not exhibit these same trends, possibly indicating better accommodation to the increased practice training loads of period B (i.e. greater fatigue resistance) or potentially indicating better adaptation to the explosiveness-focused training of period B. Furthermore, it is likely that trends associated with the concentric portion of the movement seen in athlete C (i.e. decreased relative magnitude and impulse in the acceleration-propulsion phase) may be related to the aforementioned alterations in eccentric phase mechanics, considering previous research has established a link between CMJ eccentric and concentric phase performance (Cormie et al., 2010a). In general the results of the trend analysis between the training periods indicated that the strongest (athlete A) exhibited the more favorable behavior in many characteristics following this shift (i.e. maintained JHs, increased relative magnitudes, decreased durations, maintained relative impulse and improved RFD). Conversely, the athlete with the lowest strength level (athlete C) exhibited less-desirable trends in many of the same characteristics (i.e. lower JHs, decreased relatively magnitudes, increased durations, decreased relative impulse, and decreased RFD) Interestingly, athlete B exhibits somewhat of a median trend in these same characteristics suggesting that strength may have been a determining factor in the CMJ F-t phase characteristic behavior.

The results of the examination of the magnitude of weekly changes in the CMJ F-t curve phase variables found only a few of these changes were determined to be "likely" (>75% probability) meaningful. It should be noted that criteria for determining a meaningful change was based on the SWC calculated from the reliability study (Hopkins, 2000). The reliability study was performed during a period of in-season training and competition. Thus, “likely” changes identified in this analysis can be considered to reflect either alarming levels of fatigue or worthwhile performance increases beyond the level typically observed during a season. Interpretation of these results must be considered in the context of the training process including the timing of the change as well as the training preceding any meaningful change. In general there does not seem to be a pattern between “likely” meaningful changes between athletes, as none of the athletes exhibited meaningful changes during the same weeks, and in many cases these changes are markedly different.

The results of the probability analysis highlight an interesting behavior in RFD. Although meaningful changes were only exhibited by athlete A, similar biphasic patterns were exhibited in RFD between athletes A and B. Specifically, these athletes exhibited increases and decreases in this variables at relatively the same time points (figure 5.4E). Interestingly this pattern was not observed in athlete C. The primary difference in the behavior of RFD between athletes was that athletes A and B exhibited a second peak in this characteristic during training period B, whereas athlete C did not. In fact, athlete C exhibited a statistical decrease in RFD throughout this period. Considering the behavior of RFD coincides with athlete strength levels (in both pattern and magnitude) it is possible that strength influenced the athlete’s expression of this characteristic. One potential explanation relates back to fatigue resistance. It is possible that the athletes with the greater strength levels could better tolerate training loads later in the training process, allowing these athletes to exhibit increased levels of RFD when training was shifted to explosiveness-focused training. Additionally, considering that both athletes A and B exhibited their greatest peak in RFD during training period B, it may suggest that the stronger athletes better responded to the programed shifts in training emphasis. Both theoretical and experimental evidence exist suggesting stronger individuals may better adapt to explosive-type training (Cormie et al., 2010b; Minetti, 2002; Zamparo et al., 2002). Thus, the biphasic behavior of RFD experiences in athletes A and B could be indicative of a "better" response to training.

This investigation highlights how the information obtained from these variables and specific analyses may be applied to monitoring an athlete's explosive performance state. In fact, the present analysis provides a prime example of both the utility of mechanistic variables as well as the potential pitfalls of only considering output variables when monitoring. For example, in week four athlete A exhibits a meaningful improvement in JH (figure 5.5E). However, this improvement was accompanied by a "likely" meaningful increase in duration and decreases in shape factor of the acceleration-propulsion phase (figure 5.5A and D), and although not determined meaningful, a decreased acceleration-propulsion magnitude (figure 6.6B), and the lowest RFD value of the training period (figure 5.4E). If only considering the output variable JH, it might seem as though this athlete is in an improved explosive state. However, when mechanistic variables are considered (i.e. CMJ F-t curve phase characteristics), a more complete picture of jump performance is provided suggesting the altered CMJ mechanics such as an increased countermovement depth may have resulted in the improved JH. When viewed in the context of the training process, these changes observed in athlete A coincide with end of the high-volume resistance training period. Thus, these changes in jump mechanics may be the result changes in the athletes performance state (fatigue or adaptation) as a result of the preceding training microcycles (weeks).

In conclusion, the results of the descriptive case study suggest that CMJ F-t curve phase characteristics may be effectively applied in athlete performance monitoring setting to identify changes in an athlete's explosive state by providing a mechanistic perspective of jump performance. Considering, the contrasting patterns in the behavior of these characteristics between athletes, it is likely that an athlete's strength level influences the behavior of these variables in the context of a training process. Thus, athlete's strength levels should be considered when interpreting the longitudinal behavior of CMJ F-t curve phase characteristics. Furthermore, this investigation highlighted the use of two practical methods of assessing changes in performance monitoring variables over time.

Practical Application

The results of this investigation suggest that mechanistic CMJ variables such as those obtained from CMJ F-t curve phase characteristics may be effectively used in athlete performance monitoring. In addition to monitoring changes in jump height, practitioners can also track changes in jump mechanics in the context of the training process, improving their ability to determine an athlete's performance state (fatigue, recovery, adaptation). However, prior to implementing CMJ F-t curve phase characteristics it is recommended that measures of variability be established for these measures through a reliability study. With measure of variability established coaches and practitioners can utilize analyses such as probability of meaningful changes in order to more confidently identify "real" changes, and interpret them in the context of the training process. Additionally, considering the high degree of individuality exhibited in the behavior of many variables, it is recommended that athlete performance monitoring be implemented on an individualized basis, or by grouping athletes based on common characteristics (e.g. developmental level, strength level) in order to improve how monitoring variables may be interpreted.

References

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., . . . Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *The Journal of Strength & Conditioning Research, 18*(3), 534-539. doi: 10.1519/r-13213.1

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sports & Exercise, 42*(9), 1731-1744. doi: 10.1249/MSS.0b013e3181d392e8

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine & Science in Sports & Exercise, 42*(8), 1566-1581. doi: 10.1249/MSS.0b013e3181cf818d

Day, M. L., McGuigan, M. R., Brice, G., & Foster, C. (2004). Monitoring exercise intensity during resistance training using the session RPE scale. *The Journal of Strength & Conditioning Research, 18*(2), 353-358.

Dowling, J. J., & Vamos, L. (1993). Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics, 9*, 95-95.

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., . . . Dodge, C. (2001). A new approach to monitoring exercise training. *The Journal of Strength & Conditioning Research, 15*(1), 109-115.

Garhammer, J., & Gregor, R. (1992). Propulsion forces as a function of intensity for weightlifting and vertical jumping. *The Journal of Strength & Conditioning Research, 6*(3), 129-134.

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology & Performance, 10*(1), 84-92. doi: 10.1123/ijspp.2013-0413

Gathercole, R. J., Stellingwerff, T., & Sporer, B. C. (2015). Effect of acute fatigue and training adaptation on CMJ performance in elite snowboard cross athletes. *The Journal of Strength & Conditioning Research, 29*(1), 37-46. doi: 10.1519/jsc.0000000000000622

Halson, S. L. (2014). Monitoring Training Load to Understand Fatigue in Athletes. *Sports Medicine*, 1-9.

Hamada, T., Sale, D. G., MacDougall, J. D., & Tarnopolsky, M. A. (2003). Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica*, *178*(2), 165-173. doi: 10.1046/j.1365-201X.2003.01121.x

Henry, F. M. (1967). “Best” versus “average” individual scores. *Research Quarterly. American Association for Health, Physical Education and Recreation, 38*(2), 317-320.

Hopkins, W. G. (2000). Measures of Reliability in Sports Medicine and Science. *Sports Medicine, 30*(1), 1-15. doi: 10.2165/00007256-200030010-00001

Hopkins, W. G. (2002). Probabilities of clinical or practical significance. *Sportscience 6 sportsci.org/jour/0201/wghprob.htm*.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of Performance Measurements Derived From Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency. *The Journal of Strength & Conditioning Research, 23*(3), 874-882. doi: 10.1519/JSC.0b013e3181a00ca2

Jo, E., Judelson, D. A., Brown, L. E., Coburn, J. W., & Dabbs, N. C. (2010). Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. *The Journal of Strength & Conditioning Research, 24*(2), 343-347. doi: 10.1519/JSC.0b013e3181cc22a4

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of CMJs: A methodological study. *Journal of Applied Biomechanics, 14*, 105-117.

Kraska, J. M., Ramsey, M. W., Haff, G. G., Fethke, N., Sands, W. A., Stone, M. E., & Stone, M. H. (2009). Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology & Performance, 4*(4), 461-473.

Lacey, J. I., Bateman, D. E., & Vanlehn, R. (1953). Autonomic response specificity; an experimental study. *Psychosomatic Medicine, 15*(1), 8-21.

Linthorne, N. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics, 69*, 1198.

Major, J. A., Sands, W. A., McNeal, J. R., Paine, D. D., & Kipp, R. (1998). Design, construction, and validation of a portable one-dimensional force platform. *The Journal of Strength & Conditioning Research, 12*(1), 37-41.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *The Journal of Strength & Conditioning Research, 13*(1), 58-66.

McMaster, D., Gill, N., Cronin, J., & McGuigan, M. (2014). A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine, 44*(5), 603-623. doi: 10.1007/s40279-014-0145-2

Minetti, A. E. (2002). On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *European Journal of Applied Physiology*, *86*(4), 363-369.

Mizuguchi, S. (2012). Net Impulse and Net Impulse Characteristics in Vertical Jumping (Doctoral dissertation). *East Tennessee State University, Johnson City, TN*.

Moir, G. L., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *The Journal of Strength & Conditioning Research*, *18*(2), 276-280.

Moir, G. L., Garcia, A., & Dwyer, G. (2009). Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology and Performance*, *4*(3), 317.

Moir, G. L., Sanders, R., Button, C., & Glaister, M. (2005). The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *The Journal of Strength & Conditioning Research*, *19*(1), 140-145.

Parker, R. I., Vannest, K. J., Davis, J. L., & Sauber, S. B. (2011). Combining nonoverlap and trend for single-case research: Tau-U. *Behavior Therapy*, *42*(2), 284-299.

Psycharakis, S. G., & Miller, S. (2006). Estimation of errors in force platform data. *Research Quarterly in Exercise and Sport*, *77*(4), 514-518. doi: 10.1080/02701367.2006.10599386

Seitz, L. B., de Villarreal, E. S., & Haff, G. G. (2014). The temporal profile of postactivation potentiation is related to strength level. *The Journal of Strength & Conditioning Research, 28*(3), 706-715. doi: 10.1519/JSC.0b013e3182a73ea3

Smith, T. B., & Hopkins, W. G. (2011). Variability and Predictability of Finals Times of Elite Rowers. *Medicine & Science in Sports & Exercise*, *43*(11), 2155-2160. doi: 10.1249/MSS.0b013e31821d3f8e

Sole, C. J. (2015). Analysis of the Phase Characteristics of the Countermovement Vertical Jump in Athletes (Doctoral dissertation). *East Tennessee State University, Johnson City, TN*.

Stone, M. H., Moir, G. L., Glaister, M., & Sanders, R. (2002). How much strength is necessary? *Physical Therapy in Sport, 3*(2), 88-96.

Stone, M. H., O'Bryant, H., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003). Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps. *The Journal of Strength & Conditioning Research, 17*(1), 140-147.

Stone, M. H., Sands, W. A., Pierce, K. C., Ramsey, M. W., & Haff, G. G. (2008). Power and power potentiation among strength-power athletes: preliminary study. *International Journal of Sports Physiology & Performance, 3*(1), 55-67.

Stone, M. H., Stone, M. E., & Sands, W. A. (2007). *Principles and practice of resistance training*. Champaign, IL: Human Kinetics

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of Error in Determining Countermovement Jump Height With the Impulse Method. *Journal of Applied Biomechanics, 17*, 43-54.

Taylor, K. L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. D. (2012). Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning, 20*(1), 12-23.

Taylor, K. L., Cronin, J., Gill, N. D., Chapman, D. W., & Sheppard, J. (2010). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology & Performance, 5*(4), 546-558.

Ugrinowitsch, C., Tricoli, V., Rodacki, A. L., Batista, M., & Ricard, M. D. (2007). Influence of training background on jumping height. *The Journal of Strength & Conditioning Research, 21*(3), 848-852. doi: 10.1519/r-20162.1

Winter, D. A., Sidwall, H. G., & Hobson, D. A. (1974). Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics, 7*(2), 157-159.

Yu, B., Gabriel, D., Noble, L., & An, K.-N. (1999). Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *Journal of Applied Biomechanics, 15*, 318-329.

Zamparo, P., Minetti, A. E., & di Prampero, P. E. (2002). Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: theory and facts. *European Journal of Applied Physiology, 88*(3), 193-202. doi: 10.1007/s00421-002-0691-4

CHAPTER 6

SUMMARY AND FUTURE INVESTIGATIONS

The overall purpose of this dissertation was to examine the use of an in depth analysis of the characteristics of the countermovement jump (CMJ) force-time (F-t) curve to evaluate an athlete's explosive performance state. To fulfil this purpose the following were examined as individual research projects: 1) an examination of the phase characteristics of the CMJ F-t curve between athletes based on jumping ability, 2) an examination of the influence of maximal muscular strength on the CMJ F-t curve phase characteristics of athletes, and 3) an examination of the behavior of CMJ F-t curve characteristics over the course of a training process in athletes of varying strength levels.

The results of study I indicated that a phase-by-phase analysis of the CMJ F-t curve was successful in identifying several phase characteristics common among proficient jumpers (criterion measure: jump height [JH]). Specifically, proficient jumpers were associated with greater relative magnitude in the stretching, net impulse, and acceleration-propulsion phases and greater relative impulse in the unweighted, stretching, net impulse, and acceleration-propulsion phases. Additionally, the primary difference between male and female jumpers was found to be relative phase magnitude and relative phase impulse in these same phases. An additional finding of this study was that phase duration did not statistically differ between jump performance groups or between males and females, indicating that the temporal structure of the CMJ F-t curve phases has little influence on jump performance (JH). An unexpected finding of this study was the interaction between stretching and leaving phase shape factor between jump performance groups. Specifically, more proficient jumpers exhibited greater stretching phase shape factor values relative to the leaving phase shape factor, indicating this characteristic may be important for JH. Considering the both timing and shape of the CMJ F-t curve phases were not statistically different between males and females, as well as the fact that males in general possess greater levels of muscular strength, it was speculated that the observed differences between males and females in CMJ F-t curve characteristics were related to force production capacity (i.e. muscular strength).

Numerous studies in the sport science and strength and conditioning literature have reported strong relationships between measures of strength and vertical jump performance measures including JH. Additionally, differences in relative magnitude and impulse along with the lack of sex differences in phase duration and shape found in study I indicated that strength may potentially influence CMJ F-t curve phase characteristics. Therefore, study II sought to identify the role of strength in the phase characteristics of the CMJ F-t curve. The results of study II were unable to link an athlete's level of maximal strength with characteristics of the CMJ F-t curve, with the exception of phase duration. While only present in the analysis of male athletes, *post hoc* analyses found stronger athletes (criterion measure: allometrically scaled isometric peak force) exhibited shorter duration unweighted phases as compared to less-strong athletes. In addition study II was able to provide further evidence of the existence of common phase characteristics exhibited in proficient jumpers identified in study I. Interestingly the shape of the stretching phase was again found linked to JH suggesting that movement strategies or neuromuscular capacities influencing this phase are important to jumping and consequently explosive performance.

Studies I and II of this dissertation were successful in identifying 1) characteristics of proficient jumpers influencing JH such as relative magnitude of the phases contained within positive impulse and the relative shape of the stretching phase, and 2) differences in CMJ F-t curve phase characteristics influenced by an athlete's maximal strength level (unweighted phase duration). It was concluded that monitoring these characteristics may be an effective method for assessing an athlete's performance state throughout a training process. Thus, study III sought to examine the behavior of these CMJ F-t curve phase characteristics over an entire training process. Considering several differences in training response have been identified between strong and less-strong athletes, this investigation selected to focus on three individual athletes of distinctly different strength levels. The results of this study can be summarized in the following manner. When assessing the behavior of the CMJ F-t curve phase characteristics between training phases notable trends were identified indicating the stronger athletes responded in a more favorable manner as compared to weaker athlete over the course of training (such as maintained JH and increased rate of force development [RFD]). In fact as training progressed, the weaker athlete exhibited several statistical decreases in these characteristics. Additionally, several meaningful changes in CMJ F-t curve phase characteristics were identified over the course of the training process. In general, there seemed to be no pattern in meaningful changes in these variables between athletes. However, analysis of the behavior of RFD suggested expression of this variable may be influenced by strength or stronger athletes are able to better adapt throughout the training process.

Although this dissertation was successful in answering several questions regarding CMJ F-t curve phase characteristics and how they relate to an athlete's performance state, future research is warranted to further understand how these variables may be interpreted. One of particular interest is to further establish the relationship between neuromuscular qualities of the athlete and these characteristics. Subsequent studies in this area should consider investigating the influence of additional strength qualities such as dynamic strength, and RFD on the characteristics of the CMJ F-t curve phases (for example stretching phase shape factor), both in cross-sectional and longitudinal investigations. Additionally, future research may consider identifying the effect of neuromuscular fatigue on these characteristics. Providing additional information regarding both the influence of additional measures of strength and explosiveness on the CMJ F-t curve characteristics as well as the behavior of these characteristics in response to fatigue, will greatly enhance how these characteristics may be used to monitor an athlete's performance state.

REFERENCES

Adamson, G. T., & Whitney, R. J. (1971). Critical appraisal of jumping as measure of human power *In Vredenbregt, J. (ed.), Biomechanics II, Baltimore, Md., University Park Press, p.208-211*.

Alexander, R., & Bennet-Clark, H. (1977). Storage of elastic strain energy in muscle and other tissues. *Nature, 265*(5590), 114-117.

Anderson, F. C., & Pandy, M. G. (1993). Storage and utilization of elastic strain energy during jumping. *Journal of Biomechanics, 26*(12), 1413-1427.

Andersson, H. M., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. (2008). Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. *Medicine & Science in Sports & Exercise, 40*(2), 372-380.

Balsalobre-Fernandez, C., Tejero-Gonzalez, C. M., & del Campo-Vecino, J. (2014a). Hormonal and neuromuscular responses to high-level middle- and long-distance competition. *International Journal of Sports Physiology & Performance, 9*(5), 839-844. doi: 10.1123/ijspp.2013-0539

Balsalobre-Fernandez, C., Tejero-Gonzalez, C. M., & del Campo-Vecino, J. (2014b). Relationships between training load, salivary cortisol responses and performance during season training in middle and long distance runners. *PLoS One, 9*(8), e106066. doi: 10.1371/journal.pone.0106066

Barnes, J. L., Schilling, B. K., Falvo, M. J., Weiss, L. W., Creasy, A. K., & Fry, A. C. (2007). Relationship of jumping and agility performance in female volleyball athletes. *The Journal of Strength Conditioning Research, 21*(4), 1192-1196. doi: 10.1519/r-22416.1

Berthoin, S., Dupont, G., Mary, P., & Gerbeaux, M. (2001). Predicting sprint kinematic parameters from anaerobic field tests in physical education students. *The Journal of Strength Conditioning Research, 15*(1), 75-80.

Biewener, A. A., & Roberts, T. J. (2000). Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective. *Exercise and Sport Sciences Reviews, 28*(3), 99-107.

Bissas, A. I., & Havenetidis, K. (2008). The use of various strength-power tests as predictors of sprint running performance. *Journal of Sports Medicine Physical Fitness, 48*(1), 49-54.

Bobbert, M. F., & Casius, L. J. (2005). Is the effect of a countermovement on jump height due to active state development? *Medicine &Science in Sports & Exercise, 37*(3), 440-446.

Bobbert, M. F., Gerritsen, K. G., Litjens, M. C., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? *Medicine &Science in Sports & Exercise, 28*, 1402-1412.

Bobbert, M. F., Mackay, M., Schinkelshoek, D., Huijing, P., & van Ingen Schenau, G. (1986). Biomechanical analysis of drop and countermovement jumps. *European Journal of Applied Physiology and Occupational Physiology, 54*(6), 566-573.

Bosco, C., & Komi, P. V. (1979). Mechanical characteristics and fiber composition of human leg extensor muscles. *European Journal of Applied Physiology and Occupational Physiology, 41*(4), 275-284.

Bosco, C., Tihanyi, J., Komi, P., Fekete, G., & Apor, P. (1982). Store and recoil of elastic energy in slow and fast types of human skeletal muscles. *Acta Physiologica Scandinavica, 116*(4), 343-349.

Bret, C., Rahmani, A., Dufour, A.-B., Messonnier, L., & Lacour, J.-R. (2002). Leg strength and stiffness as ability factors in 100 m sprint running. *Journal of Sports Medicine and Physical Fitness, 42*(3), 274-281.

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports Medicine, 38*(12), 1045-1063. doi: 10.2165/00007256-200838120-00007

Byrne, C., & Eston, R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Science, 20*(5), 417-425. doi: 10.1080/026404102317366672

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., . . . Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. The *Journal of Strength & Conditioning Research, 18*(3), 534-539. doi: 10.1519/r-13213.1

Cavagna, G., Saibene, F., & Margaria, R. (1965). Effect of negative work on the amount of positive work performed by an isolated muscle. *Journal of Applied Physiology, 20*(1), 157-158.

Cormack, S. J., Newton, R. U., & McGuigan, M. R. (2008). Neuromuscular and endocrine responses of elite players to an Australian rules football match. *International Journal of Sports Physiology & Performance, 3*(3), 359-374.

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Cormie, P. (2008). Neuromuscular and endocrine responses of elite players during an Australian rules football season. *International Journal of Sports Physiology & Performance, 3*(4), 439-453.

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology & Performance, 3*(2), 131-144.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *Journal of Applied Biomechanics, 24*(2), 112.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength & Conditioning Research*, *23*(1), 177-186.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Adaptations in athletic performance after ballistic power versus strength training. *Medicine & Science in Sports & Exercise, 42*(8), 1582-1598.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine & Science in Sports & Exercise, 42*(9), 1731-1744. doi: 10.1249/MSS.0b013e3181d392e8

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010c). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine & Science in Sports & Exercise, 42*(8), 1566-1581. doi: 10.1249/MSS.0b013e3181cf818d

Coutts, A. J., Reaburn, P., Piva, T. J., & Rowsell, G. J. (2007). Monitoring for overreaching in rugby league players. *European Journal of Applied Physiology*, *99*(3), 313-324. doi: 10.1007/s00421-006-0345-z

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *The Journal of Strength & Conditioning Research, 19*(2), 349-357.

Day, M. L., McGuigan, M. R., Brice, G., & Foster, C. (2004). Monitoring exercise intensity during resistance training using the session RPE scale. *The Journal of Strength & Conditioning Research, 18*(2), 353-358.

Desipres, M. (1976). Polyparametric study of the vertical jump *In, Komi, P.V. (ed.), Biomechanics V-B, Baltimore, Md., University Park Press, 1976, p. 73-80.*

Desmedt, J. E., & Godaux, E. (1977). Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *Journal of Physiology, 264*(3), 673-693.

Dowling, J. J., & Vamos, L. (1993). Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics, 9*, 95-95.

Enoka, R. M. (1995). Morphological features and activation patterns of motor units. *Journal of Clinical Neurophysiology, 12*(6), 538-559.

Enoka, R. M. (2008). *Neuromechanics of Human Movement* (4 ed.): Human Kinetics, Champaign, IL.

Ettema, G. J., Huijing, P. A., & de Haan, A. (1992). The potentiating effect of prestretch on the contractile performance of rat gastrocnemius medialis muscle during subsequent shortening and isometric contractions. *Journal of Experimental Biology, 165*, 121-136.

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., . . . Dodge, C. (2001). A new approach to monitoring exercise training. *The Journal of Strength & Conditioning Research, 15*(1), 109-115.

Freitas, V. H., Nakamura, F. Y., Miloski, B., Samulski, D., & Bara-Filho, M. G. (2014). Sensitivity of physiological and psychological markers to training load intensification in volleyball players. *Journal of Sports Science & Medicine, 13*(3), 571-579.

Fry, A. C., Ciroslan, D., Fry, M. D., LeRoux, C. D., Schilling, B. K., & Chiu, L. Z. (2006). Anthropometric and performance variables discriminating elite American junior men weightlifters. *The Journal of Strength & Conditioning Research, 20*(4), 861-866. doi: 10.1519/r-18355.1

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003). Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. *The Journal of Strength & Conditioning Research, 17*(4), 746-754.

Garhammer, J., & Gregor, R. (1992). Propulsion forces as a function of intensity for weightlifting and vertical jumping. *The Journal of Strength & Conditioning Research, 6*(3), 129-134.

Gathercole, R. J., Sporer, B. C., & Stellingwerff, T. (2015). Countermovement Jump Performance with Increased Training Loads in Elite Female Rugby Athletes. *International Journal of Sports Medicine*. doi: 10.1055/s-0035-1547262

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *International Journal of Sports Physiology & Performance, 10*(1), 84-92. doi: 10.1123/ijspp.2013-0413

Gathercole, R. J., Stellingwerff, T., & Sporer, B. C. (2015). Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *The Journal of Strength & Conditioning Research, 29*(1), 37-46. doi: 10.1519/jsc.0000000000000622

Girard, O., Lattier, G., Micallef, J. P., & Millet, G. P. (2006). Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *British Journal of Sports Medicine, 40*(6), 521-526. doi: 10.1136/bjsm.2005.023754

González-Ravé, J., Arija, A., & Clemente-Suarez, V. (2011). Seasonal changes in jump performance and body composition in women volleyball players. *The Journal of Strength & Conditioning Research, 25*(6), 1492-1501.

Gonzalez, A., Hoffman, J. R., Scallin-Perez, J., Stout, J., & Fragala, M. (2012). Performance changes in National Collegiate Athletic Association Division I women basketball players during a competitive season: Starters vs. nonstarters. *The Journal of Strength & Conditioning Research, 26*(12), 3197-3203.

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966a). Tension development in highly stretched vertebrate muscle fibres. *The Journal of physiology, 184*(1), 143-169.

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966b). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *The Journal of Physiology, 184*(1), 170-192.

Granados, C., Izquierdo, M., Ibanez, J., Ruesta, M., & Gorostiaga, E. (2008). Effects of an entire season on physical fitness in elite female handball players. *Medicine & Science in Sports & Exercise, 40*(2), 351.

Haff, G. G., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Kawamori, N., Jackson, J. R., . . . Stone, M. H. (2005). Force-Time Curve Characteristics of Dynamic and Isometric Muscle Actions of Elite Women Olympic Weightlifters. *The Journal of Strength & Conditioning Research, 19*(4), 741-748.

Haff, G. G., Stone, M. H., O'Bryant, H. S., Harman, E., Dinan, C., Johnson, R., & Han, K. (1997). Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions. *The Journal of Strength & Conditioning Research, 11*(4), 269-272.

Häkkinen, K. (1993a). Changes in physical fitness profile in female basketball players during the competitive season including explosive type strength training. *Journal of Sports Medicine & Physical Fitness, 33*(1), 19-26.

Häkkinen, K. (1993b). Changes in physical fitness profile in female volleyball players during the competitive season. *Journal of Sports Medicine & Physical Fitness, 33*(3), 223-232.

Halson, S. L. (2014). Monitoring Training Load to Understand Fatigue in Athletes. *Sports Medicine*, 1-9.

Hamada, T., Sale, D. G., MacDougall, J. D., & Tarnopolsky, M. A. (2003). Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica*, *178*(2), 165-173. doi: 10.1046/j.1365-201X.2003.01121.x

Henry, F. M. (1952). Force-time characteristics of the sprint start. *Research Quarterly. American Association for Health, Physical Education and Recreation, 23*(3), 301-318.

Henry, F. M. (1967). “Best” versus “average” individual scores. *Research Quarterly. American Association for Health, Physical Education and Recreation, 38*(2), 317-320.

Hochmuth, G. (1984). *Biomechanics of Athletic Movement*. Berlin: Sportverlag.

Hoffman, J. R., Fry, A. C., Howard, R., Maresh, C. M., & Kraemer, W. J. (1991). Strength, speed and endurance changes during the course of a division I basketball season. *The Journal of Strength & Conditioning Research, 5*(3), 144-149.

Hoffman, J. R., Maresh, C. M., Newton, R. U., Rubin, M. R., French, D. N., Volek, J. S., . . . Kraemer, W. J. (2002). Performance, biochemical, and endocrine changes during a competitive football game. *Medicine & Science in Sports & Exercise, 34*(11), 1845-1853. doi: 10.1249/01.mss.0000035373.26840.f8

Hoffman, J. R., Nusse, V., & Kang, J. (2003). The effect of an intercollegiate soccer game on maximal power performance. *Canadian Journal of Applied Physiology, 28*(6), 807-817.

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, 65-70.

Hopkins, W. G. (2000). Measures of Reliability in Sports Medicine and Science. *Sports Medicine, 30*(1), 1-15. doi: 10.2165/00007256-200030010-00001

Hopkins, W. G. (2002). Probabilities of clinical or practical significance. *Sportscience 6 sportsci.org/jour/0201/wghprob.htm*.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of Performance Measurements Derived From Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency. *The Journal of Strength & Conditioning Research, 23*(3), 874-882. doi: 10.1519/JSC.0b013e3181a00ca2

Hortobagyi, T., Lambert, N., & Kroll, W. (1991). Voluntary and reflex responses to fatigue with stretch-shortening exercise. *Canadian Journal of Sport Science, 16*(2), 142-150.

Howell, M. L. (1956). Use of force-time graphs for performance analysis in facilitating motor learning. *Research Quarterly. American Association for Health, Physical Education and Recreation, 27*(1), 12-22.

Hunebelle, G., & Damoiseau, J. (1973). Medicine and Sport, vol. 8: Biomechanics III, pp. 417-425 (Karger, Basel 1973). *Biomechanics III, 3*, 417.

Jo, E., Judelson, D. A., Brown, L. E., Coburn, J. W., & Dabbs, N. C. (2010). Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. *The Journal of Strength & Conditioning Research, 24*(2), 343-347. doi: 10.1519/JSC.0b013e3181cc22a4

Juneja, H., Verma, S., & Khanna, G. (2010). Isometric Strength and Its Relationship to Dynamic Performance: A Systematic Review. *Journal of Exercise Science and Physiotherapy, 6*(2), 60-69.

Kawakami, Y., Muraoka, T., Ito, S., Kanehisa, H., & Fukunaga, T. (2002). In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. *The Journal of Physiology, 540*(2), 635-646.

Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O'Bryant, H. S., . . . Haff, G. G. (2006). Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *The Journal of Strength & Conditioning Research, 20*(3), 483-491. doi: 10.1519/18025.1

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics, 14*, 105-117.

Kirby, T. J., McBride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *Journal of Applied Biomechanics, 27*(3), 207-214.

Klavora, P. (2000). Vertical-jump tests: A critical review. *Strength & Conditioning Journal, 22*(5), 70-75.

Knudson, D. V. (2009). Correcting the Use of the Term “Power” in the Strength and Conditioning Literature. *The Journal of Strength & Conditioning Research, 23*(6), 1902-1908 1910.1519/JSC.1900b1013e3181b1907f1905e1905.

Kraemer, W. J., Fry, A. C., Rubin, M. R., Triplett-McBride, T., Gordon, S. E., Koziris, L. P., . . . Fleck, S. J. (2001). Physiological and performance responses to tournament wrestling. *Medicine & Science in Sports & Exercise, 33*(8), 1367-1378. doi: 10.1097/00005768-200108000-00019

Kraska, J. M., Ramsey, M. W., Haff, G. G., Fethke, N., Sands, W. A., Stone, M. E., & Stone, M. H. (2009). Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology & Performance, 4*(4), 461-473.

Krustrup, P., Zebis, M., Jensen, J. M., & Mohr, M. (2010). Game-induced fatigue patterns in elite female soccer. *The Journal of Strength & Conditioning Research, 24*(2), 437-441. doi: 10.1519/JSC.0b013e3181c09b79

Kurokawa, S., Fukunaga, T., & Fukashiro, S. (2001). Behavior of fascicles and tendinous structures of human gastrocnemius during vertical jumping. *Journal of Applied Physiology, 90*(4), 1349-1358.

Kurokawa, S., Fukunaga, T., Nagano, A., & Fukashiro, S. (2003). Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. *Journal of Applied Physiology*, 95(6):2306-14.

Lacey, J. I., Bateman, D. E., & Vanlehn, R. (1953). Autonomic response specificity; an experimental study. *Psychosomatic Medicine, 15*(1), 8-21.

Laffaye, G., Wagner, P. P., & Tombleson, T. I. L. (2014). Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables. *The Journal of Strength & Conditioning Research, 28*(4), 1096-1105. doi: 10.1519/JSC.0b013e3182a1db03

Lees, A., Vanrenterghem, J., & Clercq, D. D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, *37*(12), 1929-1940.

Levine, T. R., & Hullett, C. R. (2002). Eta Squared, Partial Eta Squared, and Misreporting of Effect Size in Communication Research. *Human Communication Research, 28*(4), 612-625. doi: 10.1111/j.1468-2958.2002.tb00828.x

Linthorne, N. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics, 69*, 1198.

Lloyd, R. S., Oliver, J., Hughes, M. G., & Williams, C. A. (2011). Specificity of test selection for the appropriate assessment of different measures of stretch-shortening cycle function in children. *Journal of Sports Medicine & Physical Fitness, 51*(4), 595-602.

Major, J. A., Sands, W. A., McNeal, J. R., Paine, D. D., & Kipp, R. (1998). Design, construction, and validation of a portable one-dimensional force platform. *The Journal of Strength & Conditioning Research, 12*(1), 37-41.

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *The Journal of Strength & Conditioning Research, 18*(3), 551-555.

Marques, M. C., Gil, H., Ramos, R. J., Costa, A. M., & Marinho, D. A. (2011). Relationships between vertical jump strength metrics and 5 meters sprint time. *Journal of Human Kinetics, 29*, 115-122. doi: 10.2478/v10078-011-0045-6

Marques, M. C., Izquierdo, M., Van den Tillaar, R., Moir, G. L., Sanchez-Medina, L., & Gonzalez-Badillo, J. J. (2014). The reliability of force-time variables recorded during vertical jump performance and their relationship with jump height in power trained athletes. *International Sports Medicine Journal, 15*(2), 146-155.

Marques, M. C., Tillaar, R., Vescovi, J. D., & Gonzalez-Badillo, J. J. (2008). Changes in strength and power performance in elite senior female professional volleyball players during the in-season: a case study. *The Journal of Strength & Conditioning Research, 22*(4), 1147-1155. doi: 10.1519/JSC.0b013e31816a42d0

McBride, J. M., Kirby, T. J., Haines, T. L., & Skinner, J. (2010). Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. *International Journal of Sports Physiology & Performance, 5*(4), 484-496.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *The Journal of Strength & Conditioning Research, 13*(1), 58-66.

McGuigan, M. R., & Winchester, J. B. (2008). The Relationship Between Isometric and Dynamic Strength in College Football Players. *Journal of Sports Science & Medicine, 7*(1), 101-105.

McGuigan, M. R., Winchester, J. B., & Erickson, T. (2006). The importance of isometric maximum strength in college wrestlers. *Journal of Sports Science & Medicine, 5*(CSSI), 108-113.

McLean, B. D., Coutts, A. J., Kelly, V., McGuigan, M. R., & Cormack, S. J. (2010). Neuromuscular, endocrine, and perceptual fatigue responses during different length between-match microcycles in professional rugby league players. *International Journal of Sports Physiology & Performance, 5*(3), 367-383.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011a). Markers of postmatch fatigue in professional Rugby League players. *The Journal of Strength & Conditioning Research, 25*(4), 1030-1039. doi: 10.1519/JSC.0b013e3181cc22cc

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011b). The role of rate of force development on vertical jump performance. *The Journal of Strength & Conditioning Research, 25*(2), 379-385. doi: 10.1519/JSC.0b013e3181be305c

McMaster, D., Gill, N., Cronin, J., & McGuigan, M. (2014). A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine, 44*(5), 603-623. doi: 10.1007/s40279-014-0145-2

Miller, A. E. J., MacDougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *European Journal of Applied Physiology and Occupational Physiology, 66*(3), 254-262. doi: 10.1007/BF00235103

Miller, D. I., & East, D. J. (1976). Kinematic and kinetic correlates of vertical jumping in women *In Biomechanics v-B, Baltimore, University Park Press., 1976, p.65-72.*

Minetti, A. E. (2002). On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *European Journal of Applied Physiology, 86*(4), 363-369.

Mizuguchi, S. (2012). Net Impulse and Net Impulse Characteristics in Vertical Jumping (Doctoral dissertation). *East Tennessee State University, Johnson City, TN*.

Moir, G. L., Button, C., Glaister, M., & Stone, M. H. (2004). Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. *The Journal of Strength & Conditioning Research, 18*(2), 276-280.

Moir, G. L., Garcia, A., & Dwyer, G. (2009). Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *International Journal of Sports Physiology & Performance, 4*(3), 317.

Moir, G. L., Sanders, R., Button, C., & Glaister, M. (2005). The influence of familiarization on the reliability of force variables measured during unloaded and loaded vertical jumps. *The Journal of Strength & Conditioning Research, 19*(1), 140-145.

Moir, G. L., Shastri, P., & Connaboy, C. (2008). Intersession reliability of vertical jump height in women and men. *The Journal of Strength & Conditioning Research, 22*(6), 1779-1784.

Newton, R. U., Rogers, R. A., Volek, J. S., Häkkinen, K., & Kraemer, W. J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *The Journal of Strength & Conditioning Research, 20*(4), 955-961.

Nimphius, S. (2011). Monitoring Neuromuscular Fatigue in Amateur Baseball Players During a National Tournament. *Journal of Australian Strength Conditioning, 19*, 110-114.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2012). Changes in muscle architecture and performance during a competitive season in female softball players. *The Journal of Strength & Conditioning Research, 26*(10), 2655-2666.

Nindl, B. C., Leone, C. D., Tharion, W. J., Johnson, R. F., Castellani, J. W., Patton, J. F., & Montain, S. J. (2002). Physical performance responses during 72 h of military operational stress. *Medicine & Science in Sports & Exercise, 34*(11), 1814-1822. doi: 10.1097/00005768-200211000-00019

Nuzzo, J. L., McBride, J. M., Cormie, P., & McCaulley, G. O. (2008). Relationship between countermovement jump performance and multi -joint isometric and dynamic tests of strength. *The Journal of Strength & Conditioning Research, 22*(3), 699-707.

Oliver, J., Armstrong, N., & Williams, C. (2008). Changes in jump performance and muscle activity following soccer-specific exercise. *Journal of Sports Science, 26*(2), 141-148.

Parker, R. I., Vannest, K. J., Davis, J. L., & Sauber, S. B. (2011). Combining nonoverlap and trend for single-case research: Tau-U. *Behavior Therapy, 42*(2), 284-299.

Payne, A., Slater, W., & Telford, T. (1968). The use of a force platform in the study of athletic activities. A preliminary investigation. *Ergonomics, 11*(2), 123-143.

Peterson, M. D., Alvar, B. A., & Rhea, M. R. (2006). The contribution of maximal force production to explosive movement among young collegiate athletes. *The Journal of Strength & Conditioning Research, 20*(4), 867-873.

Psycharakis, S. G., & Miller, S. (2006). Estimation of errors in force platform data. *Research Quarterly in Exercise & Sport, 77*(4), 514-518. doi: 10.1080/02701367.2006.10599386

Rassier, D. E. (2009). Molecular basis of force development by skeletal muscles during and after stretch. *Molecular Cell Biomechanics, 6*(4), 229-241.

Richter, C., O'Connor, N. E., Marshall, B., & Moran, K. (2014a). Analysis of characterizing phases on waveform: an application to vertical jumps. *Journal of Applied Biomechanics, 30*(2), 316-321. doi: 10.1123/jab.2012-0218

Richter, C., O'Connor, N. E., Marshall, B., & Moran, K. (2014b). Analysis of Characterizing Phases on Waveforms: An Application to Vertical Jumps. *Journal of Applied Biomechanics, 30*(2), 316-321.

Ronglan, L. T., Raastad, T., & Børgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine Science & Sports, 16*(4), 267-273. doi: 10.1111/j.1600-0838.2005.00474.x

Sands, W. A. (1991). Monitoring the elite female gymnast. *Strength & Conditioning Journal, 13*(4), 66-72.

Sargent, D. A. (1921). The physical test of a man. *American Physical Education Review, 26*(4), 188-194.

Seitz, L. B., de Villarreal, E. S., & Haff, G. G. (2014). The temporal profile of postactivation potentiation is related to strength level. *The Journal of Strength & Conditioning Research, 28*(3), 706-715. doi: 10.1519/JSC.0b013e3182a73ea3

Smith, T. B., & Hopkins, W. G. (2011). Variability and Predictability of Finals Times of Elite Rowers. *Medicine & Science in Sports & Exercise, 43*(11), 2155-2160. doi: 10.1249/MSS.0b013e31821d3f8e

Sole, C. J. (2015). Analysis of the Phase Characteristics of the Countermovement Vertical Jump in Athletes (Doctoral dissertation). *East Tennessee State University, Johnson City, TN*.

Sole, C. J., Mizuguchi, S., Suchomel, T. J., Sands, W. A., & Stone, M. H. (2014). Longitudinal monitoring of countermovement jump mechanical variables: A preliminary investigation. *In proceedings of: XXXII Congress of the International Society of Biomechanics in Sports, Johnson City, Tennessee*.

Stone, M. H., Moir, G. L., Glaister, M., & Sanders, R. (2002). How much strength is necessary? *Physical Therapy in Sport, 3*(2), 88-96.

Stone, M. H., O'Bryant, H., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003a). Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps. *The Journal of Strength & Conditioning Research, 17*(1), 140-147.

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003b). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *The Journal of Strength & Conditioning Research, 17*(1), 140-147.

Stone, M. H., Sands, W. A., Carlock, J., Callan, S., Dickie, D., Daigle, K., . . . Hartman, M. (2004). The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *The Journal of Strength & Conditioning Research, 18*(4), 878-884. doi: 10.1519/14874.1

Stone, M. H., Sands, W. A., Pierce, K. C., Carlock, J., Cardinale, M., & Newton, R. U. (2005). Relationship of maximum strength to weightlifting performance. *Medicine & Science in Sports & Exercise, 37*(6), 1037-1043.

Stone, M. H., Sands, W. A., Pierce, K. C., Ramsey, M. W., & Haff, G. G. (2008). Power and power potentiation among strength-power athletes: preliminary study. *International Journal of Sports Physiology & Performance, 3*(1), 55-67.

Stone, M. H., Stone, M. E., & Sands, W. A. (2007). *Principles and Practice of Resistance Training*. Champaign, IL: Human Kinetics

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of Error in Determining Countermovement Jump Height With the Impulse Method. *Journal of Applied Biomechanics, 17*, 43-54.

Tabachnick, B. G., & Fidell, L. S. (2007). *Experimental Designs using ANOVA*: Thomson/Brooks/Cole.

Taylor, K. L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. D. (2012). Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning, 20*(1), 12-23.

Taylor, K. L., Cronin, J., Gill, N. D., Chapman, D. W., & Sheppard, J. (2010). Sources of variability in iso-inertial jump assessments. *International Journal of Sports Physiology & Performance, 5*(4), 546-558.

Thomas, C., Jones, P. A., Rothwell, J., Chiang, C.-Y., & Comfort, P. (2015). An Investigation into the Relationship between Maximum Isometric Strength and Vertical Jump Performance. *The Journal of Strength & Conditioning Research*. (published ahead of print).

Thomas, C., Mather, D., & Comfort, P. (2014). Changes in sprint, change of direction and jump performance during a competitive season in male lacrosse players. *Journal of Athletic Enhancement, 3*(5), 1-8.

Thorlund, J. B., Aagaard, P., & Madsen, K. (2009). Rapid muscle force capacity changes after soccer match play. *International Journal of Sports Medicine, 30*(4), 273-278. doi: 10.1055/s-0028-1104587

Thorlund, J. B., Michalsik, L., Madsen, K., & Aagaard, P. (2008). Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scandinavian Journal of Medicine Science & Sports, 18*(4), 462-472.

Ugrinowitsch, C., Tricoli, V., Rodacki, A. L., Batista, M., & Ricard, M. D. (2007). Influence of training background on jumping height. *The Journal of Strength & Conditioning Research, 21*(3), 848-852. doi: 10.1519/r-20162.1

Vaverka, F., & Janura, M. (1997). Comparison of the force-time structure of the vertical jump between men and women. *In proceedings of the XV Congress of the International Society of Biomechanics in Sports*.

Vizcaya, F. J., Viana, O., del Olmo, M. F., & Acero, R. M. (2009). Could the deep squat jump predict weightlifting performance? *The Journal of Strength & Conditioning Research, 23*(3), 729-734. doi: 10.1519/JSC.0b013e3181a04dc3

Welsh, T. T., Alemany, J. A., Montain, S. J., Frykman, P. N., Tuckow, A. P., Young, A. J., & Nindl, B. C. (2008). Effects of intensified military field training on jumping performance. *International Journal of Sports Medicine, 29*(1), 45-52. doi: 10.1055/s-2007-964970

Winter, D. A., Sidwall, H. G., & Hobson, D. A. (1974). Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics, 7*(2), 157-159.

Winter, E. M. (2005). Jumping: Power or Impulse? (Letter). *Medicine & Science in Sports & Exercise, 37*(3), 523-523. doi: 10.1249/01.MSS.0000155703.50713.26

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine, 38*(3), 285-288. doi: 10.1136/bjsm.2002.002071

Young, W. B., Pryor, J. F., & Wilson, G. J. (1995). Effect of Instructions on characteristics of Countermovement and Drop Jump Performance. *The Journal of Strength & Conditioning Research, 9*(4), 232-236.

Yu, B. (1998). Determination of the appropriate cutoff frequency in the digital filter data smoothing procedure (Master's thesis) *Kansas State University, Manhattan, KS*.

Yu, B., Gabriel, D., Noble, L., & An, K.-N. (1999). Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *Journal of Applied Biomechanics, 15,* 318-329.

Zamparo, P., Minetti, A. E., & di Prampero, P. E. (2002). Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: theory and facts. *European Journal of Applied Physiology, 88*(3), 193-202. doi: 10.1007/s00421-002-0691-4

Zehr, E. P., & Sale, D. G. (1994). Ballistic movement: muscle activation and neuromuscular adaptation. *Canadian Journal of Applied Physiology, 19*(4), 363-378.

APPENDICES

APPENDIX A: ETSU Institutional Review Board Approval

East Tennessee State University
Office for the Protection of Human Research Subjects • Box 70565 • Johnson City, Tennessee 37614-1707
Phone: (423) 439-6053 Fax: (423) 439-6060

IRB APPROVAL – Initial Expedited Review

December 12, 2013

Christopher Sole

Re: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.
IRB#:c1013.20s
ORSPA #:

The following items were reviewed and approved by an expedited process:

- new protocol submission xform, CV of PI, informed consent document version 10/9/13

On **November 21, 2013**, a final approval was granted for a period not to exceed 12 months and will expire on **November 20, 2014**. The expedited approval of the study will be reported to the convened board on the next agenda.

The following **enclosed stamped, approved Informed Consent Documents** have been stamped with the approval and expiration date and these documents must be copied and provided to each participant prior to participant enrollment:

- consent version 10/9/2013 stamped approved 11/21/2013

Federal regulations require that the original copy of the participant's consent be maintained in the principal investigator's files and that a copy is given to the subject at the time of consent.

Projects involving Mountain States Health Alliance must also be approved by MSHA following IRB approval prior to initiating the study.

Unanticipated Problems Involving Risks to Subjects or Others must be reported to the IRB (and VA R&D if applicable) within 10 working days.

Proposed changes in approved research cannot be initiated without IRB review and approval. The only exception to this rule is that a change can be made prior to IRB approval when necessary to eliminate apparent immediate hazards to the research subjects [21 CFR 56.108 (a)(4)]. In such a case, the IRB must be promptly informed of the change following its implementation (within 10

Accredited Since December 2005

working days) on Form 109 (www.etsu.edu/irb). The IRB will review the change to determine that it is consistent with ensuring the subject's continued welfare.

Sincerely,
Brian C. Martin, Ph.D., Vice-Chair
ETSU Campus IRB

cc: Satoshi Mizuguchi

East Tennessee State University
Office for the Protection of Human Research Subjects • Box 70565 • Johnson City, Tennessee 37614-1707
Phone: (423) 439-6053 Fax: (423) 439-6060

IRB APPROVAL – Continuing Expedited Review

November 14, 2014

Christopher Sole

Re: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.
IRB#: c1013.20s
ORSPA#: n/a

The following items were reviewed and approved by an expedited process:

- xform 107, narrative portion of new protocol submission, previously approved ICD, modification request with revised ICD (version 9/10/14 stamped approved 9/19/14), Informed Consent Document (version 9/10/14, stamped approved 11/13/14)

On **November 13, 2014**, a final approval was granted for a period not to exceed 12 months and will expire on **November 12, 2015**. The expedited approval of the study will be reported to the convened board on the next agenda.

The following **enclosed stamped, approved ICD** has been stamped with the approval and expiration date and this document must be copied and provided to each participant prior to participant enrollment:

- Informed Consent Document **(**consent version 9/10/2014 stamped approved 11/13/2014**)**

Federal regulations require that the original copy of the participant's consent be maintained in the principal investigator's files and that a copy is given to the subject at the time of consent.

Unanticipated Problems Involving Risks to Subjects or Others must be reported to the IRB (and VA R&D if applicable) within 10 working days.

Proposed changes in approved research cannot be initiated without IRB review and approval. The only exception to this rule is that a change can be made prior to IRB approval when necessary to eliminate apparent immediate hazards to the research subjects [21 CFR 56.108 (a)(4)]. In such a

Accredited Since December 2005

case, the IRB must be promptly informed of the change following its implementation (within 10 working days) on Form 109 (www.etsu.edu/irb). The IRB will review the change to determine that it is consistent with ensuring the subject's continued welfare.

Sincerely,
Stacey Williams, PhD, Chair
ETSU Campus IRB

APPENDIX B: Informed Consent Document

Principal Investigator: Christopher J. Sole

Title of Project: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.

SUBJECT CONSENT FORM FOR PARTICIPATION OF HUMAN SUBJECTS IN RESEARCH

Project Title:	**Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.**
Primary Investigator:	Christopher J. Sole, MS, Exercise & Sport Sciences, solecj@goldmail.etsu.edu
Faculty Advisor:	Satoshi Mizuguchi, PhD, Exercise & Sport Sciences, harahara10@hotmail.com
Co-Investigator:	Kimitake Sato, PhD, Exercise & Sport Sciences, satok1@etsu.edu
Co-Investigator:	Michael Stone, PhD, Exercise & Sport Sciences, stonem@etsu.edu
Phone:	423-439-5138

INTRODUCTION:
This informed consent will explain about being a participant of this research project. Please read this consent carefully and decide if you wish to participate in this study.

PURPOSE:
The purpose of this study is observing vertical jump performance over time and observing how this measure may change throughout the training year. Additionally, this study seeks to determine the effects of specific phases of the training year (e.g. pre-season, competition phase, spring season) on vertical jump performance.

DURATION:
This study will use monitoring data that has been previously collected as well as data currently being and will be collected during the 2013-2014 and 2014-2015 academic years.

PROCEDURES:
If you agree to participate in this research, the researchers will retrieve some previously collected data from the long-term athlete monitoring database, as well as athlete monitoring data that is currently being and will be collected. Additionally, team and individual match performance statistics will be retrieved from ETSUbucs.com examined. The data that will be retrieved from the athlete monitoring database and ETSUbucs.com are:

- Results of your Isometric mid-thigh pulls, squat and countermovement jumps from pervious, current, and future long-term athlete monitoring.
- Total amount of work performed during strength and conditioning sessions.
- Total amount of time elapsed during strength and conditioning sessions, volleyball practice and competitions.
- Your rate of perceived exertion (RPE) scores obtained following competition and training sessions, and
- Team and individual match performance statistics (ETSUbucs.com).

POSSIBLE RISKS/DISCOMFORTS:
The only potential risk from participating in this study is loss of confidentiality. If you become uncomfortable having your data included in this study you may withdraw your data at any time.

POSSIBLE BENEFITS:
There is no immediate direct benefit to you as a participant in this study. The results of this study may benefit future athletes and your future performance if you continue to compete by helping with better planning and monitoring procedures.

Principal Investigator: Christopher J. Sole

Title of Project: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.

CONFIDENTIALITY:
Every attempt will be made to see that your retrieved data are kept confidential. A copy of the records from this study will be stored in a password-protected computer and locked file cabinet in the locked sport science laboratory E113 Mini-dome for at least 5 years after the end of this research. Data retrieved for and generated from this research is only accessible by the primary and co-investigators. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, the Secretary of the Department of Health and Human Services, the ETSU IRB, and personnel particular to this research have access to the study records. Your records will be kept completely confidential according to current legal requirements. They will not be revealed unless required by law, or as noted above.

FINANCIAL COSTS:
There are NO financial costs to you, and NO compensation for your participation.

VOLUNTARY PARTICIPATION:
Participation in this study involves allowing your long-term athlete monitoring data to be included in additional analysis. There are NO alternative procedures. Participation is voluntary. Choosing not to participate in this study will not affect your involvement in the long-term athlete monitoring program. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. A copy of this form will be given to you to retain for future reference.

CONTACT FOR QUESTIONS:
If you have any questions, problems or research-related medical problems at any time, you may call Christopher Sole at 908/902-5229, or Dr. Kimi Sato at 423/439-5138, or Dr. Mike Stone at 423/439-4375. You may call the Chairman of the Institutional Review Board at 423/439-6054 for any questions you may have about your rights as a research subject. If you have any questions or concerns about the research and want to talk to someone independent of the research team or you can't reach the study staff, you may call an IRB Coordinator at 423/439-6055 or 423/439/6002.

Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. The copy of this informed consent will be given after signing this form.

____

Participant's Signature Date

____

Participant's name (please print)

____

Primary Investigator's Signature Date

APPROVED
By the ETSU IRB

SEP 19 2014

By ________
Chair/IRB Coordinator

DOCUMENT VERSION EXPIRES

NOV 20 2014

ETSU IRB

Principal Investigator: Christopher J. Sole

Title of Project: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.

SUBJECT CONSENT FORM FOR PARTICIPATION OF HUMAN SUBJECTS IN RESEARCH

Project Title:	**Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.**
Primary Investigator:	Christopher J. Sole, MS, Exercise & Sport Sciences, solecj@goldmail.etsu.edu
Faculty Advisor:	Satoshi Mizuguchi, PhD, Exercise & Sport Sciences, harahara10@hotmail.com
Co-Investigator:	Kimitake Sato, PhD, Exercise & Sport Sciences, satok1@etsu.edu
Co-Investigator:	Michael Stone, PhD, Exercise & Sport Sciences, stonem@etsu.edu
Phone:	423-439-5138

INTRODUCTION:
This informed consent will explain about being a participant of this research project. Please read this consent carefully and decide if you wish to participate in this study.

PURPOSE:
The purpose of this study is observing vertical jump performance over time and observing how this measure may change throughout the training year. Additionally, this study seeks to determine the effects of specific phases of the training year (e.g. pre-season, competition phase, spring season) on vertical jump performance.

DURATION:
This study will use monitoring data that has been previously collected as well as data currently being and will be collected during the 2013-2014 and 2014-2015 academic years.

PROCEDURES:
If you agree to participate in this research, the researchers will retrieve some previously collected data from the long-term athlete monitoring database, as well as athlete monitoring data that is currently being and will be collected. Additionally, team and individual match performance statistics will be retrieved from ETSUbucs.com examined. The data that will be retrieved from the athlete monitoring database and ETSUbucs.com are:

- Results of your Isometric mid-thigh pulls, squat and countermovement jumps from pervious, current, and future long-term athlete monitoring.
- Total amount of work performed during strength and conditioning sessions.
- Total amount of time elapsed during strength and conditioning sessions, volleyball practice and competitions.
- Your rate of perceived exertion (RPE) scores obtained following competition and training sessions, and
- Team and individual match performance statistics (ETSUbucs.com).

POSSIBLE RISKS/DISCOMFORTS:
The only potential risk from participating in this study is loss of confidentiality. If you become uncomfortable having your data included in this study you may withdraw your data at any time.

POSSIBLE BENEFITS:
There is no immediate direct benefit to you as a participant in this study. The results of this study may benefit future athletes and your future performance if you continue to compete by helping with better planning and monitoring procedures.

APPROVED
By the ETSU IRB
NOV 13 2014
By aa
Chair/IRB Coordinator

DOCUMENT VERSION EXPIRES
NOV 12 2015
ETSU IRB

Principal Investigator: Christopher J. Sole

Title of Project: Monitoring vertical jump force-time curve characteristics during different phases of the training year in NCAA D-I women's volleyball players.

CONFIDENTIALITY:
Every attempt will be made to see that your retrieved data are kept confidential. A copy of the records from this study will be stored in a password-protected computer and locked file cabinet in the locked sport science laboratory E113 Mini-dome for at least 5 years after the end of this research. Data retrieved for and generated from this research is only accessible by the primary and co-investigators. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, the Secretary of the Department of Health and Human Services, the ETSU IRB, and personnel particular to this research have access to the study records. Your records will be kept completely confidential according to current legal requirements. They will not be revealed unless required by law, or as noted above.

FINANCIAL COSTS:
There are NO financial costs to you, and NO compensation for your participation.

VOLUNTARY PARTICIPATION:
Participation in this study involves allowing your long-term athlete monitoring data to be included in additional analysis. There are NO alternative procedures. Participation is voluntary. Choosing not to participate in this study will not affect your involvement in the long-term athlete monitoring program. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. A copy of this form will be given to you to retain for future reference.

CONTACT FOR QUESTIONS:
If you have any questions, problems or research-related medical problems at any time, you may call Christopher Sole at 908/902-5229, or Dr. Kimi Sato at 423/439-5138, or Dr. Mike Stone at 423/439-4375. You may call the Chairman of the Institutional Review Board at 423/439-6054 for any questions you may have about your rights as a research subject. If you have any questions or concerns about the research and want to talk to someone independent of the research team or you can't reach the study staff, you may call an IRB Coordinator at 423/439-6055 or 423/439/6002.

Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. The copy of this informed consent will be given after signing this form.

____
Participant's Signature   Date

____
Participant's name (please print)

____
Primary Investigator's Signature   Date

APPROVED
By the ETSU IRB
NOV 13 2014
By aa
Chair/IRB Coordinator

DOCUMENT VERSION EXPIRES
NOV 12 2015
ETSU IRB

VITA

CHRISTOPHER J. SOLE

Education:	Ph.D. Sport Physiology and Performance, East Tennessee State University, Johnson City, TN, 2015
	M.S. Exercise Science, East Stroudsburg University of Pennsylvania, East Stroudsburg, PA, 2009
	B.S. Exercise Science (*Magna Cum Laude*), Manhattan College, Riverdale, NY, 2008
	Middletown High School South, Middletown, NJ, 2004
Professional Experience:	Sport Scientist/Strength and Conditioning Coach, East Tennessee State University Women's Volleyball, 2012-2014
	Adjunct Faculty, Marjorie K. Unterberg School of Nursing and Health Studies, Monmouth University, 2011-2012
	Adjunct Faculty, Department of Health and Exercise Science, County College of Morris, 2010
Publications:	Sole, C. J., Moir, G. L., Davis, S. E., & Witmer, C. A. (2013). Mechanical analysis of the acute effects of a heavy resistance exercise warm-up on agility performance in court-sport athletes. *Journal of Human Kinetics*, 39(1), 147-156.
Honors and Awards:	Outstanding Research Poster, 9th Annual CESSCE Coaches College, East Tennessee State University, 2014
	Outstanding Graduate Student Assistant Award, Claudius G. Clemmer College of Education, Department of Exercise and Sport Sciences, East Tennessee State University, 2014
	ESPN the Magazine All-Academic First Team All-District, Manhattan College, 2007 & 2008